
Proceedings of:

The Economies of Precision Engineering

*(Error Budgeting of Manufacturing Processes and the
Influence of Measurement Uncertainty on “As Built”
Manufactured Components)*

2009 Summer Topical Meeting

July 7 and 8, 2009

*Embassy Suites East Peoria Hotel
East Peoria, Illinois*

The American Society for Precision Engineering (ASPE) is a multidisciplinary professional and technical society concerned with research and development, design, manufacture and measurement of high accuracy components and systems. ASPE activities encompass relevant aspects of mechanical, electronic, optical and production engineering, physics, chemistry, and computer and materials science. Membership is open to anyone interested in any aspect of precision engineering.

Founded in 1986, ASPE provides a new focus for a diverse but important community. Other professional organizations have covered aspects of precision engineering, always as a sideline to their principal goals. ASPE is based on the core of generic concepts necessary to achieve precision in any application; independent of discipline, ASPE intends to be the focus for precision technology, and to represent all facets from research to application.

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Preface

This book comprises the proceedings of the 2009 Summer Topical Meeting. The contributions reflect the authors' opinions and are published as presented to ASPE, without change. Their inclusion in this publication does not necessarily constitute endorsement by the ASPE, or its editorial staff.

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ISBN 978-1-887706-50-6

2009

American Society for Precision Engineering
301 Glenwood Avenue, Suite 205
Raleigh, NC 27603

Printed in the United States of America

2009 Summer Topical Meeting

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2009 Summer Topical Meeting

Meeting Schedule

	Tuesday, July 7		Wednesday, July 8
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8:15	TECHNICAL SESSION I	8:30	TECHNICAL SESSION V
10:00		9:45	
	Coffee Break		Coffee Break
10:30	TECHNICAL SESSION II	10:15	TECHNICAL SESSION VI
11:45		11:30	
	Lunch		Lunch
1:15	TECHNICAL SESSION III	1:15	TECHNICAL TOUR: CATERPILLAR TRACK-TYPE TRACTOR ASSEMBLY FACILITY
3:00		3:00	
	Refreshment Break		
3:30	TECHNICAL SESSION IV		
4:45			
	Free Time		
5:30	KEYNOTE ADDRESS		
6:30			
6:45	DINNER		

Foreword

This meeting will focus on error budgeting of manufacturing processes with the goal of improving final part quality. Properly designed and maintained manufacturing processes will yield best quality components at optimal cost. Measurement uncertainty is a key element in determining manufacturing process parameters and will be a secondary topic of the meeting.

The objective of this meeting is to bring together researchers and practitioners from industry, government and academia to provide a forum for the exchange of ideas. It is anticipated that this subject will attract participants who are not currently active in the ASPE. We encourage the attendance of non-ASPE members and look forward to their contribution.

2009 Summer Topical Meeting Program Committee:

Meeting Co-Chairmen:

Paulo H. Pereira and Dean E. Beutel
Caterpillar Inc.

Keynote Address

James (Jim) D. Waters

Vice President, Caterpillar Inc.

*An Executive View of Precision Engineering
Tying As Built Component Quality to Business Profitability*

Tuesday, July 7, 2009, 5:30 to 6:30 p.m.



James D. Waters, Jr., became Vice President of the Caterpillar Production Center of Excellence on December 1, 2005. This division is leading an enterprise transformation of manufacturing systems to help set a "gold standard" for quality, safety, and speed in industry. Jim is providing leadership to this enterprise effort, drawing on his strong systems and process skills as well as his product and manufacturing management experience gained in Japan, the UK, and the US.

Jim joined Caterpillar in 1978 as an engineering co-op trainee. After graduating from Iowa State University in 1981 with a BS in Electrical Engineering, he worked in manufacturing where he was responsible for the development and implementation of vision-based robotic welding technology. He was appointed Factory Superintendent/Manufacturing Engineering Manager, and three years later moved to Japan's Shin Caterpillar Mitsubishi (a joint venture between Caterpillar and Mitsubishi Heavy Industries) hydraulic excavator development. He has held numerous positions ranging from coordinating manufacturing plans for hydraulic excavator manufacturing in France, United States, Belgium, and Japan to Component Design Department Manager.

In 1994, Jim accepted the position of Managing Director of Production, and with it the responsibility for Manufacturing Operations in Sagami and Akashi, Japan. At that time, he also became a Board Member for Shin Caterpillar Mitsubishi. He moved to England in 1996, where he had direct responsibility for all building and construction equipment manufactured and/or sold into Europe including factories in Leicester and Stockton, England.

In 2002, Jim became General Manager of the Hydraulics and Hydraulic Systems business in Joliet, Illinois. He was responsible for the company's hydraulic components and integrated systems, including operations in Joliet, IL; Sumter, SC; and Jesi, Italy.

Waters holds a patent, which he received in 1985, for algorithms related to adaptive welding.

Jim is Past Chairman of the Engineering College Industrial Advisory Council at Iowa State University and Co-chairman of the Rialto Square Theater Capital Campaign. Jim serves on the ASME National Advisory Board. He is also a Board Member for Akoya, Inc. Jim has been a long time supporter of the Juvenile Diabetes Research Foundation, and is currently serving as a member of the Community Advisory Panel for the Central Illinois Walk to Cure Diabetes.

He and his wife, Karleen, have two children (Jill and Steven) and reside in Peoria, Illinois where he enjoys the theater, volunteer work, and traveling. Jim speaks Japanese, although he does not consider himself fluent.

Technical Papers



A S P E

Technical Sessions

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Session Chair: Dean E. Beutel (Caterpillar Inc.)

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ECONOMICS OF MEASUREMENT UNCERTAINTY AND TOLERANCES

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INTRODUCTION

Economic growth, whether that of a national economy or of a particular industry, is often modeled as a production function relating output (Y) to input factors of production such as hours of labor (L) and capital investment (C). The Cobb-Douglas production function [1] given in equation (1) is a simple and common example, and is sufficient to illustrate our discussion. The exponents α and β describe the influence of the input factors; with $\alpha, \beta > 0$ and typically $\alpha + \beta \approx 1$. The magnitude of the coefficient A , known as total factor productivity (TFP), scales with human capital (worker training and education) and the state of employed technology.

$$Y = AL^{\alpha}C^{\beta} \quad (1)$$

Developing economies grow rapidly because they can increase all three of these quantities: the productive labor force increases as rural population become factory workers, capital spending creates new infrastructure such as improved roads, bridges, and machinery, and TFP increases as workers gain better training, education, and adopt new technology.

In advanced economies, such as the United States, the labor force is largely developed and is changing only incrementally. Similarly, domestic infrastructure is well developed and while additional capital investments can improve output – and increase the national competitive advantage – it is not a strategic advantage because any nation with access to capital can create infrastructure, i.e. there is no barrier to replication of this advantage.

In developed economies, a strategic competitive advantage is gained primarily by adopting new technology (including new management methods) that increase output and are not easily duplicated. That is, a strategic advantage arises from working smarter, as opposed to working

harder (increasing L) or by constantly purchasing new tools (increasing C). Although competitive advantage creates high value-added products, even the best defended advantage eventually “leaks out” and becomes nullified. Hence, today’s high value-added manufacturing becomes tomorrow’s commoditized product. High value products imply manufacturing strategies and practices that exclude competitors. This involves intellectual capital that is protected either as knowledge (patents, trade secrets) or processes (unique facilities, deep institutional knowledge within the organization). In this paper, we are primarily interested in developing and exploiting deep knowledge about the manufacturing process in order to optimize it and increase profits.

MEASUREMENT ADDED VALUE

In manufacturing, a persistent factor in the exclusion of competitors is the ability to produce increasingly complex components, with both higher accuracy and lower cost, which also drives product quality metrics such as improved function and higher reliability. One aspect of higher accuracy and lower cost in precision manufacturing involves optimizing the metrology process on an economic basis. This involves knowledge of the product production distribution, the measurement process distribution, and the consequences of bad decisions – e.g. rejecting in-specification components or accepting out-of-specification components.

Recently a number of national and international standards including the ASME B89.7 series [2] and the ISO 14253 [3] series have addressed some of the probabilistic aspects of this issue. We use this particular concept as an example of working smarter by optimizing this aspect of the measurement process.

While it is sometimes claimed that measurements “do not add value” this is only true in the case that *a priori* there is 100 %

certainty that all components are produced within specification. In the more typical case, some fraction of components are out-of-specification and identifying and eliminating them reduces a host of potential costs such as increased warranty expense, loss of customers due to dissatisfaction, decreased brand value, and potential lawsuits. Ideally, all of these effects can be captured in cost functions that express the cost of making various incorrect decisions. Hence, in reality, metrology's role is to identify and minimize "negative value" components produced in the manufacturing process, whether that is expensive scrap or – generally more expensive – downstream problems created from out-of-specification components.

In addition to the basic function of culling out-of-specification components from the manufacturing output, measurements are increasingly being used to control the manufacturing process. Process control is highly desirable as it not only reduces the number of measurements (and hence costs), but it proactively adjusts the process and thus can reduce the number of out-of-specification components, i.e. improves the production distribution. The cost functions are now "leveraged up" as a few process control measurements may affect several hundred manufactured components. Additionally, an erroneous measurement system now has the opportunity to misadjust the manufacturing parameters creating out-of-specification components and then pass them onto the customer. Hence the stakes (cost functions) are much higher for process control measurements than for inspection measurements.

MANUFACTURING OPTIMIZATION

In an ideal world, the entire manufacturing endeavor, from design, production, inspection, to post-purchase support, would be economically optimized. For example, there are obvious cost tradeoffs between design tolerances and production costs, or between production quality and post-purchase expenses (warranty costs etc.). As manufacturing processes become increasingly understood, and as data acquisition, storage, and computation costs have dramatically declined, new opportunities for optimizing the manufacturing process are emerging. By recognizing this new technological environment, strategic competitive advantage can be captured through increasing

the TFP to yield more and higher quality output for the same labor and capital costs.

Recently, some aspects of the above scenario are being realized. In this paper we focus on progress on optimizing the "gauging limits" that set the measurement threshold for accepting or rejecting components. Additionally, we discuss the current progress on optimizing the entire measurement process to further reduce costs.

GAUGING LIMITS

The industrial revolution accelerated with the invention of interchangeable parts. For the majority of the nineteenth century this involved hard gauges (at that time often called limit gauges) that were the physical embodiment of workpiece tolerances. Toward the end of the nineteenth century analog measuring instruments such as calipers and micrometers became increasingly available and thus required comparing the instrument's output value against numerical limits (i.e. tolerances) on the workpiece drawing. Acceptable workpieces had measured values at or within the tolerance zone – a decision rule now known as "simple acceptance"; see Figure 1 [4].

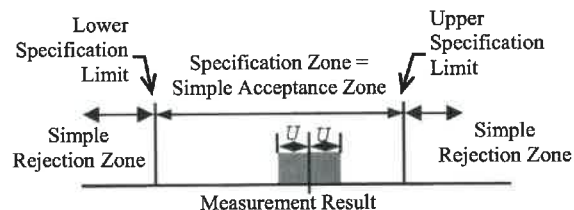


FIGURE 1. An example of simple acceptance and rejection. The measurement uncertainty interval is of width $2U$, where U is the expanded ($k = 2$) uncertainty.

In the latter half of the twentieth century the uncertainty of measurements became more important as requirements on tolerances steadily decreased and global interchangeability requirements increased. More recently, the distinction between the acceptance limits (also known as the gauging limits) and the specification limits (tolerance limits) have become more significant. The difference between the two sets of limits is known as the guard band. If the gauging limits are inside the specification limits the resulting decision rule is known as "stringent acceptance"; see Figure 2 [4]. If the gauging limits are outside the specification zone then this increases the size of

the acceptance zone and is known as “relaxed acceptance”; see Figure 3 [4].

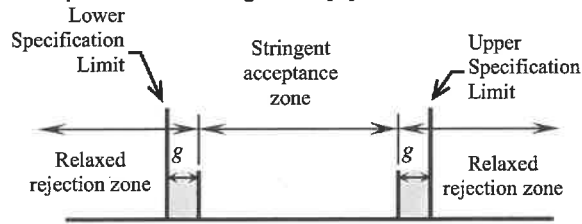


FIGURE 2. A stringent acceptance zone for measured components, the offsets between the specification limits and the acceptance limits is the guard band g .

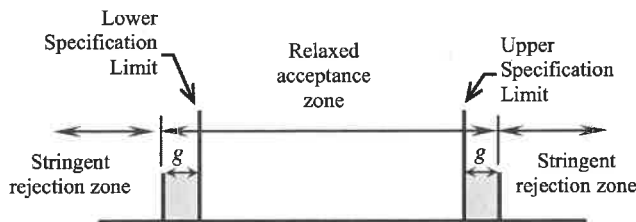


FIGURE 3. A relaxed acceptance zone for measured components; components with measured values beyond the specification limit may be accepted.

Allowing this new degree of freedom, where specification and gauging limits are no longer identical, creates the opportunity to increase profits by exploiting our knowledge about the metrology and manufacturing process, as we illustrate next.

OPTIMIZING DECISION RULES

To illustrate the advantage of working smarter by making better decisions we provide the following example. Consider a manufacturing process that has a production capability index of $2/3$, i.e. $C_p = 0.66$, where $C_p = T/(6u_p)$, T is the component tolerance and u_p is one standard deviation of the production distribution. Suppose also that the measurement capability index is 2 , i.e. $C_m = 2$, where $C_m = T/(4u_m)$, and u_m is one standard uncertainty of the measurement system. (This is sometimes referred to as a $2:1$ gauging ratio.) For example, the inspection might be done with a high speed automated digital camera that rapidly images and computes the measurement result of the component.

The cost model for this example is given in Table 1. In this example, the net profit of accepting an in-specification component is \$1.

The net loss of rejecting a component is \$1 (it does not matter if the component is in-specification or out-of-specification, in either case the loss is the same). We examine three cases of accepting an out-of-specification component. In case A, the consequences are minor and the loss is \$2, e.g. minor customer dissatisfaction costs. In case B, the loss is \$10, perhaps due to increased warranty costs as a result of defective components. In case C, the loss is \$20 which might represent both warranty costs and customer dissatisfaction.

TABLE 1. The profit matrix showing the profit or loss for each decision

	In-specification	Out-of-specification
Accepted	+1	Case A: -2 Case B: -10 Case C: -20
Rejected	-1	-1

In Table II we present six different decision rules ranging from no inspection – which is equivalent to 100 % acceptance (i.e. relaxed rejection with an infinite guard band) – to stringent acceptance with a guard band equal to 100 % of the expanded measurement uncertainty. This latter rule is the ISO 14253-1 default rule. For each rule, the probabilities of the four decision outcomes are presented and the economic consequences of the cost functions (given in Table I) are shown.

For this particular example, when the costs associated with accepting an out-of-specification component are minor (case A) then relaxed (75 % U) acceptance is the economically optimal decision. Conversely, when the cost of accepting an out-of-specification component is high (case C), then the economics shifts to stringent (25 % U) acceptance.

OPTIMIZING METROLOGY SYSTEMS

We have illustrated through the previous example how increased profits can be derived by optimizing the decision rule, i.e. setting the gauging limits. But this example naturally gives rise to more questions such as “how is the information needed to compute the process and measurement capability indices acquired?” and “what additional parameters can be profitably optimized?”

TABLE 2. The outcome matrix showing the probability of accepting or rejecting either an in-specification or out-of-specification component for various decision rules. The net profit for each of the rules and cases are also shown, the most profitable outcome is shown in bold.

	100 % U Stringent Acceptance	25 % U Stringent Acceptance	0 % U Simple Acceptance	25 % U Relaxed Acceptance	75 % U Relaxed Acceptance	No Inspection
Accept / In-specification	0.625	0.873	0.991	0.934	0.9499	0.9545
Accept / Out-of-specification	0.00035	0.007	0.013	0.019	0.0354	0.0455
Reject / In-specification	0.328	0.080	0.041	0.021	0.0024	NA
Reject / Out-of-specification	0.047	0.041	0.0035	0.027	0.0123	NA
Net Profit per 1000 pieces						
Case A: cost = 2	249.1	738.3	809.4	846.7	864.4	863.5
Case B: cost = 10	246.3	683.1	706.4	682.8	581.2	499.5
Case C: cost = 20	242.8	614.1	577.7	477.9	227.2	44.5

Fortunately, a confluence of computer hardware, software and sensor technology have recently converged to address these issues. Hence the ability to understand and reconfigure complex manufacturing systems – previously requiring human thought and intuition – is now becoming accessible to more rigorous and accurate computation.

The measurement capability index, C_m , can now be computed in detail for complex 3D coordinate measuring machine (CMM) measurements using computer simulation. This technology can take into detailed account the specific parametric errors of the measuring instrument performance, the geometric imperfections of the workpiece (i.e. form errors), the thermal environment's influence on both the instrument and the workpiece, the metrologist's selected measurement plan (the number and location of measurement points), and the complex nature of the feature under measurement which is often related to other features via datum reference frames. A rigorous evaluation of all of these effects is beyond a single human's cognitive capabilities, but can be computed using Monte Carlo simulation [5].

Given that the details of the measurement process can be simulated, it follows that the cost functions of this process can also be determined. For example, different CMMs have different accuracies and also operational costs, e.g., due to costs of capital equipment and the level of operator training. Similarly, different measurement plans have different costs since increasing the number of measurement points increases the inspection time; conversely, increasing the CMM speed reduces the run time but also (potentially) the accuracy. These and other costs can be estimated and therefore

included in the optimization process. Hence, we anticipate in the near future that the capability to compute the optimal CMM, measurement plan, thermal environment, and gauging limits (i.e. decision rule) that yields the maximal economic profits.

This type of deep insight into the fundamental nature of the manufacturing endeavor becomes a strategic competitive advantage for the firm that can capture and develop this knowledge. By successively increasing and exploiting these insights, the TFP can be steadily increased thus yielding higher productivity in a manner that is not easily replicated. We view this approach as the vanguard of the future high value-added manufacturing firm.

REFERENCES

- [1] Cobb, C.W., Douglas, P.H., "A Theory of Production", American Economic Review, 18, 139-165 (1928).
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- [3] Available from at www.iso.org
- [4] ASME B89.7.3.1-2001, Guidelines for Decision Rules: Considering Measurement Uncertainty in Determining Conformance to Specifications, www.asme.org
- [5] J.M. Baldwin, K.D. Summerhays, D.A. Campbell, R.P. Henke, "Application of Simulation Software to Coordinate Measurement Uncertainty Evaluations", Measure, 2(4), 40-52 (2007).

GEAR METROLOGY VS. MEASURING UNCERTAINTY - FUNCTIONAL AND ELEMENTAL MEASUREMENT CONSIDERATIONS

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Bohemia, NY 11716

The presentation serves to proliferate the measurement practices of both functional and analytical or elemental Involute gear and spline tooth measurement and the practical consideration of measuring uncertainty with respect to the geometric tooth form, gear blank form, and related 3D measurements on cylindrical spur and helical external and internal gears and splines.

What is covered:

- What is a gear and spline?
- Types of Gearing
- Gear nomenclature
- Gear Blank Position & Form
- Gear Blank Surface Texture Irregularities
- Gear Size & Length
- Gear Measurements - Functional - Size, Composite, & Analytical Measurement Uncertainty- Budgeting and Application before measurement or gaging selection
- Chart Interpretations
- Process Troubleshooting- Types of Errors: Cause & Effect: e.g. Tooth Distortions caused by material or heat-

treat?

- Future Considerations

The goal of this presentation is for attendees to walk away with:

- Everyone leaves with an understanding of the practice of gear and spline metrology and the uncertainty budgeting process and practical application of gaging.
- Everyone will see the types of instruments and machines used to measure gears for blank form-roundness, diameter-size, tooth thickness, geometric gear tooth form measurements: Fa-involute profile, Fb-helix/lead, Fp-index, fp-pitch, Fr-Runout, Sn-tooth thickness, DOB-Mdk, DOP-Mdr and how the gear blank form, tooth size, tooth form and surface finish errors impacts the quality of your products.
- Ideas are generated and a Q&A session will follow to discuss real world challenges in today's manufacturing and source receiving environments.

CHOOSING THE TASK-ADEQUATE METROLOGY EQUIPMENT FOR GEAR INSPECTION ON THE SHOP FLOOR

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Americas Operations Division – East Peoria
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INTRODUCTION

In order to achieve the correct level of manufacturing performance, it is very important to properly plan for all the tasks involved in the process. That includes making the parts or components but also inspecting/measuring them for conformance to the intended design specifications. It is relatively common for inspection tasks to be considered as less important than manufacturing ones. Kunzmann et al. [1] shows that can be costly given improper planning and implementation of measurement systems may significantly hinder overall process capability for the given manufacturing cell.

The critical decision in planning a measurement process is to define what level of capability is necessary in order to achieve the correct balance between overall costs and performance since better accuracy metrology equipment is generally more expensive up front but a cheaper solution may cost more over the long run. There are many options when choosing measurement techniques ranging from a simple measuring tape to a latest generation high accuracy coordinate measuring machine (CMM). FIGURE 1 quantitatively illustrates the cost versus benefit relationship for metrology options.

The cost for a hand gage is relatively small compared to that of a CMM. However, a hand gage, like a plug gage or a micrometer, does not have the same capabilities as a CMM. Nonetheless, for certain applications, like for example measuring a steel plate thickness at a first operations area, a vernier caliper is better suited than a CMM. In the end, the application must dictate the proper gage based on feature types, associated tolerances and volume of parts to be measured.

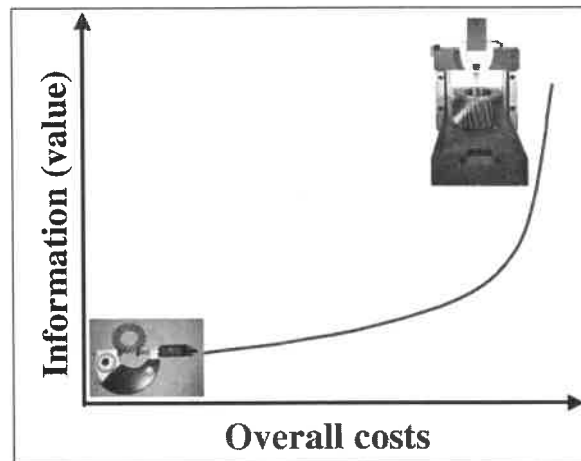


FIGURE 1. Illustration of cost versus benefit for measurement techniques

One of the main criteria to choose a suitable measuring device (or gage) for an application is that it can measure the needed features with a certain chosen tolerance to uncertainty ratio (TUR). This ratio used to be 10:1 (gagemaker's rule) [2] for quite a long time and many still use it. The requirement a gage needs to have tighter specifications than the feature it is supposed to measure is needed to minimize the influence of measurement equipment errors on the measurand results which are used to verify conformance to design intent. In reality, the proper ratio is a choice driven by a multitude of reasons that need to be considered including technical as well as business ones [3]. It is more commonplace nowadays smaller ratios down to 4:1 due to the continuous tightening of required tolerance levels.

INFLUENCE OF MEASUREMENT UNCERTAINTY ON MANUFACTURING PROCESSES

In simulating the influence of uncertainty on process parameters, it was possible to obtain results showing it. FIGURE 2 has the results of such a simulation. Three data sets of different nominal c_{pk} values were created and, to each,

three different levels of TUR were applied to then calculate the apparent c_{pk} values, i.e., the values a measuring device would obtain. Uncertainty levels of 10 %, 25 % and 50 % corresponding to TURs of 10:1, 4:1 and 2:1 were used with different sample sizes to calculate the process parameters. Sample sizes between 5 % and 25 % showed no clear influences on the results. TUR, on the other hand, had a very significant negative impact on the apparent c_{pk} values. The better the process, the more the uncertainty influenced the final c_{pk} values.

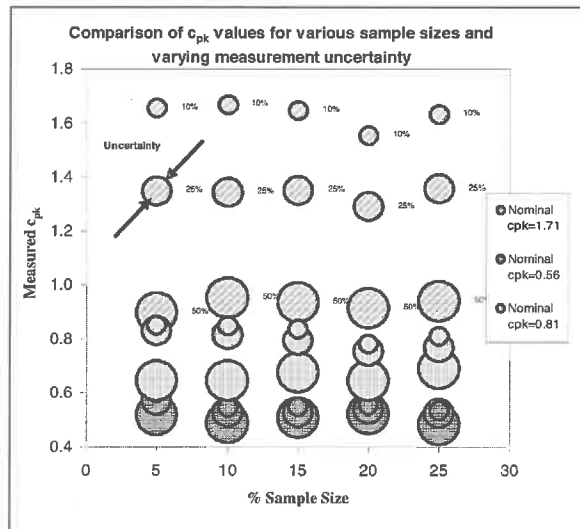


FIGURE 2. Simulation of uncertainty influence on process parameters

These results validate the 10:1 TUR since at that level, the influence on the process is minimal. At the 4:1 TUR, the influence is much more pronounced pointing to the need to choose at what level to hold it based on the specific conditions.

METROLOGY PLANNING FOR MANUFACTURING CELL

Early on during the planning stage of a new manufacturing cell it was determined that due to volume and flow of parts, it was preferred to have all the measurements performed at the cell area. Also, a decision was made to minimize the work done by the cell operator to inspect the parts – this reduced the choices to some sort of automated measuring system.

To determine what kind of metrology solution to employ, uncertainty budgets [[4], [5]] were developed for the tightest toleranced features to be manufactured at the cell. For that, some

different options were considered including shop floor and laboratory CMMs as well as gear checkers. The last were soon eliminated due to the more complicated setups and the limited capabilities to measure features other than gear geometry. Part and measurement system thermal effects were considered. Not surprisingly, thermal effects came out as very large contributors to measurement uncertainty due to the application being on the shop floor and the relatively tight tolerances.

So called shop floor coordinate measuring machine models were considered for the application but even the most modern ones currently available could not handle the possible temperature variations present at the location. At the location where the cell was installed, the daily temperature variation averages about 12 °C per day during the five warmest months of the year according to weather data. Those are the months when the shop floor is not controlled for temperature (it is during colder months). The shop floor CMM models considered at the time had a maximum allowable variation of 8 K per day. Nonetheless, two of these shop floor models were used for the uncertainty estimation exercise assuming they could perform under the location conditions. Moreover, shop floor metrology solutions usually do not present a very effective way to deal with changing temperatures of the parts.

The uncertainty budgets were done considering three conditions for part temperature being the same for all four CMM models used in the exercise. Two of the CMMs were shop floor models and two were laboratory versions from two different vendors. Parts with initial temperature values of 40 °C, 28 °C and 25 °C were considered. The same cycle time was used for all four machine models. Higher initial part temperature certainly meant more temperature variation during the measurement cycle. Several different features were considered for the overall study with the results of two shown by TABLE 1. These were the results for one internal and one external diameter corresponding to the measurement between pins for a ring gear and the measurement over pins of an external one.

It was clear the thermally induced uncertainties were the dominant factors for the conditions studied. The laboratory machines performed better than the shop floor counterparts because they have tighter specifications. That is mainly

because the smaller temperature variations allow for a more stable CMM structure. It is also worth mentioning the TUR values were mostly smaller than 10:1 for the tighter tolerances encountered for the parts in this project.

TABLE 1 – Uncertainty and TUR values

		"shop floor" machines		laboratory machines (18-22°C)	
		model 1	model 2	model 3	model 4
OD = 502 mm	Unc @ 40 °C	119.91	118.75	91.49	91.48 μ m
	TUR	1.3	1.3	1.7	1.7
	Unc @ 28 °C	85.61	85.14	59.76	59.75 μ m
	TUR	1.9	1.9	2.7	2.7
	Unc @ 25 °C	45.61	45.45	39.24	39.23 μ m
	TUR	3.5	3.5	4.1	4.1
ID = 345 mm	Unc @ 40 °C	82.41	81.62	62.88	62.88 μ m
	TUR	4.5	4.6	5.9	5.9
	Unc @ 28 °C	58.84	58.52	41.08	41.08 μ m
	TUR	6.3	6.4	9.1	9.1
	Unc @ 25 °C	31.36	31.25	29.49	29.49 μ m
	TUR	11.9	11.9	12.6	12.6

Because most of the results had patterns similar to these, it was necessary to temperature control the parts prior to measurement. Consequently, it made sense, from a technical point of view, to also place the CMM inside a controlled environment. The financial analysis also supported the enclosed machine with automation solution.

Upon completing the uncertainty budgets, a Pugh analysis was used to compare the three possible options for measuring the parts made by the cell: 1) taking them to a metrology laboratory; 2) shop floor CMM; 3) enclosed CMM. TABLE 2 below has the results. Placing a high degree of importance on measurement uncertainty, the logical solution was to have an enclosed CMM at the cell.

The final solution was to place a laboratory CMM inside an enclosure located at the manufacturing cell and a dual-pallet system to move the parts from the outside, through a cooling chamber, into the machine volume for the measurement to take place and finally, out for retrieval by the users. FIGURE 3 has a picture of the implemented system which details the pallet in front of the thermally controlled enclosure. The far left and far right stations are for loading. Immediately next to them (towards the center) there are two cooling stations, one on each side. A part, once at the cooling station, has its thermal state monitored by a contact sensor and temperature controlled air blasted onto it for stabilization. The parts stay in this

position until a temperature threshold is reached when they are ready to move to the center station and onto the CMM (provided no other part is being measured at the moment). The chosen threshold was 24 °C which was an acceptable compromise between cost (time) and performance.

TABLE 2 – Pugh analysis

Criteria	Importance Rating	Concept 1 - As-is (Metrology Lab)	Concept 2 - Shop floor machines	Concept 3 - Enclosed machines
Measurement uncertainty	9	9	1	9
Cost of implementation	1	9	1	3
Long term cost	1	3	3	3
Ease of use	3	1	9	3
Risk	3	1	3	9
Flow of parts	9	1	9	3
	totals	108	130	150



FIGURE 3 – Frontal view of measuring system

AUTOMATED ESTIMATION OF UNCERTAINTY VALUES

To facilitate the estimation of measurement uncertainty for CMMs and other automated measuring equipment, it would be very useful to have the software running it capable of estimating uncertainty values. The software

could use a library of details about parts, CMMs, styli and the like to estimate the values. A programmer could use that tool to quickly estimate uncertainties while programming offline and then adjust the measurement strategies based on the TUR results. Besides optimizing for uncertainties, programmers could also optimize for velocity (throughput) of the measurements. Programmers normally make decisions about measurement strategy when creating programs based on their technical experience and knowledge about the specific part and process. A tool such as this estimator could improve an experienced programmer's output and facilitate the work of a novice one. It could also be used to compare similar solutions in the case multiple choices are available, particularly when procuring a new system.

CONCLUSIONS

Proper (part) tolerance to (measurement) uncertainty ratio (TUR) is a primary requirement in order to obtain useful feature information. Improper measurements create inefficiencies and potentially serious quality problems. When planning a manufacturing process, due consideration must be given to the metrology equipment to properly support the operation. Otherwise, the process parameter targets may not be achieved even though the manufacturing operations may have been correctly designed and implemented.

The example described shows it is possible to plan for metrology in parallel with the manufacturing operations in order to achieve the intended outcome.

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EVOLUTION OF THE RENISHAW PRODUCTIVITY SYSTEM™

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The presentation will discuss the history behind the development of Renishaw's UK based manufacturing system. After a brief introduction to the company, its history and the various product divisions, the presentation will focus on the challenges that the company faced in its manufacturing operations as it experienced rapid growth during the early 90's. The decision to develop a highly automated manufacturing operation, had a profound and far reaching impact on all aspects of the companies operations ranging from design through to the final assembly of the product.

This presentation will focus on the disciplines and equipment that were developed to implement a highly automated machining operation, capable of running unmanned for over 140 hours per machine. The system is called RAMTIC (Renishaw Automated Milling Turning and Inspection Center) and is designed to produce a complete batch of components

necessary for the production of a given Renishaw product, including final inspection on the machine tool, without manual intervention of any sort.

The presentation will discuss the impact that this had on product design, process control, tooling selection, choice of machine tool and product cost.

The manufacturing engineering disciplines necessary to ensure that the process control loop is maintained and understood are discussed; including the challenges presented by the changing thermal environment (machining is not completed in a 20 deg C environment). The traceability of on machine measurement for final inspection of dimensional conformance, using the same metrology structure that machined the part is discussed together with some of the uncertainty of measurement estimations that were completed.

MANAGEMENT OF MEASUREMENT UNCERTAINTY IN CALIBRATION

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INTRODUCTION

Measurement uncertainty can be a useful management tool. A properly developed uncertainty analysis provides the critical information needed to make data based decisions regarding measurement systems. An uncertainty analysis can highlight opportunities to get the largest return on an investment to a measurement process, whether that investment is new equipment, modification to measurement process, environmental control, or calibration services. In the calibration industry, an uncertainty analysis can be used to show how uncertainty in one calibration impacts subsequent measurement processes. Instead of following an arbitrary rule-of-thumb in selecting measurement processes, such as a 4:1 rule or similar, uncertainty management allows for a better balance between cost of calibration and the required uncertainty. In this paper, issues and opportunities with the management of measurement uncertainty are examined, in particular from the perspective of a calibration service provider.

MEASUREMENT UNCERTAINTY

Table 1 shows a simple example analysis of measurement uncertainty that follows the principles of the ISO Guide to the Expression of Uncertainty in Measurement, the *GUM* [1]. The measurement is the calibration of the diameter of a 10" plug gage following the U.S. standard ASME B89.1.5-1998 [2]. Table 1 lists sources of uncertainty and the estimated standard uncertainty for each. The combined and expanded uncertainty is also shown.

Measurement uncertainty is a technical tool that captures the influences to the quality of a specific measurement and then represents that quality in a quantitative manner. In the example shown in Table 1, the diameter is being measured by mechanical comparison to a calibrated gage block in a temperature controlled laboratory environment. The first two sources of uncertainty listed in Table 1 represent the equipment used in the calibration process, including their accuracy specifications and

uncertainty of their calibration. The third source of uncertainty represents the quality of the laboratory environment by capturing the influence of the ambient temperature of the lab; the impact of which depends on the difference in the coefficient of thermal expansion of the test equipment and the plug gage being calibrated. The fourth source of uncertainty is the temperature difference between the test equipment and the plug gage, which is impacted not only by the laboratory temperature control but also by the calibration procedure. Finally, the last source of uncertainty considers the operator skill and additional variation created by the measurement process.

TABLE 1. Example measurement uncertainty for calibrating the diameter of a 10" plug gage.

Uncertainty Source	Standard Uncertainty (μinches)
Gage block calibration uncertainty	11.5
Instrument accuracy specification	5.8
Ambient temperature and the difference in the coefficient of thermal expansion	8.7
Difference in the temperature	6.6
Operator and process repeatability	2.0
Combined and expanded uncertainty using k=2	34 μin

PROCESS IMPROVEMENT TOOL

Most commercial calibration laboratories are accredited to ISO/IEC 17025 [3]. To achieve accreditation, the measurement uncertainty must be suitably estimated for all calibrations. Proper measurement uncertainty estimation may be a technical challenge and is sometimes seen as the final objective, but uncertainty can be a useful business tool for making data based decisions on difficult topics. Since the

measurement uncertainty analysis captures the influence of the test equipment and its calibration, the laboratory environment, and the operator variation in a quantitative manner, the uncertainty can then be used as a tool for process improvement.

As an example, say an organization has decided to calibrate Class X plug gages using the equipment and process represented by the uncertainty in Table 1. The tolerance for the diameter of a 10" plug gage of Class X is ± 100 μ inches [2]. If the laboratory is following a calibration practice that requires their uncertainty to be less than some fraction of the tolerance, they may determine the ratio of that tolerance to their uncertainty. This ratio is the *TUR*, or test uncertainty ratio, which is well described in the U.S. standard ANSI/NCSL Z540.3-2006 [4] as

$$TUR = \frac{T}{U} \quad (1)$$

where *U* is the combined and expanded uncertainty and *T* is the accuracy tolerance. For measuring equipment, this tolerance *T* is often expressed as a maximum permissible error, or *MPE* [5].

For this example, with a tolerance of ± 100 μ inches, and an expanded uncertainty of ± 34 μ inches, the *TUR* would be 2.9. It is not uncommon for calibration laboratories to have a required minimal *TUR* of 4, the so-called 4:1 rule (see [4] or [6]). In this case, the uncertainty would not meet a *TUR* requirement of 4:1.

To reduce the measurement uncertainty, the uncertainty analysis can be examined to determine the most cost effective solution. Since the calibration uncertainty of the gage blocks is the largest contributor to the uncertainty shown in Table 1, the first recommendation may be to find a new source for the calibration of the gage blocks with a lower uncertainty. The cost of this change is easily determined. The second largest source of uncertainty is the laboratory temperature. Improving the environment may be very expensive, but it may be possible to study the laboratory space and find a location when the temperature control is better than the rest of the laboratory. The cost of this study and moving equipment may be minimal.

Table 2 shows the improved measurement uncertainty for the same measurement process but with a new gage block calibration source and

a slightly improved temperature control. With the improvements, the *TUR* has been increased from 2.9 to 4.3, which would make the uncertainty acceptable to the organization.

TABLE 2. Improved measurement uncertainty for calibrating the diameter of a 10" plug gage.

Uncertainty Source	Standard Uncertainty (μ inches)
Gage block calibration uncertainty	5.5
Instrument accuracy specification	5.8
Ambient temperature and the difference in the coefficient of thermal expansion	4.3
Difference in the temperature	6.6
Operator and process repeatability	2.0
Combined and expanded uncertainty using k=2	23 μ in

CONFORMANCE DECISION RULES

ASME B89.7.3.1 [7] discusses the simple acceptance decision rule with an N:1 *TUR*. Simple acceptance is a type of conformance decision rule. If the N:1 *TUR* is achieved then it may be stated that any measured values within the tolerance limits are considered acceptable, and any results outside the limits are not acceptable.

Another decision rule discussed in [7] is stringent acceptance, where the measurement uncertainty is used as a guard band to reduce the acceptance zone. This decision rule is the default rule of ISO 14253-1 [8] and is also discussed for ISO/IEC 17025 accredited labs in ILAC G8 [9]. Another approach to decision rules is to manage the risk of false accept or reject. The application of probabilistic risk analysis for measurement decisions can be found in many industries (for example, see [4] or [10]).

The choice of conformance decision rule will impact the required measurement uncertainty and therefore the cost of a measurement process. The choice is not a measurement issue but is a business decision regarding acceptable risk.

UNCERTAINTY MANAGEMENT

One problem with decision rules that are based on tolerances and uncertainty is that they do not consider the use of the measurement. Calibration measurements are a unique type of measurement that are only performed on other measuring equipment. Measurement equipment is only calibrated if it is to be used, or has been used, for additional subsequent measurements. By managing the uncertainty of this subsequent measurement, the impact of the uncertainty of the calibration can be determined.

Table 3 shows a measurement uncertainty analysis for the calibration of an outside micrometer at 25 mm using Grade AS-1 gage blocks [11]. The tolerance for Grade AS-1 blocks is $\pm 0.3 \mu\text{m}$. The uncertainty is estimated when the gage blocks are calibrated to grade (by some external calibration provider) using both a 4:1 *TUR* and also a 2:1 *TUR*, the later of which would be considered unacceptable following a 4:1 *TUR* rule. Both results are shown in Table 3.

The results in Table 3 show that the “unacceptably calibrated” gage blocks only increase the measurement uncertainty for this micrometer calibration by about 3.6% over the use of the “acceptably calibrated” gage blocks. If the *MPE* for the micrometer is $\pm 2 \mu\text{m}$, then the *TUR* for this calibration would be either 4.19 or 4.04, depending on which gage block calibration source was used. If the goal for the micrometer calibration is to have a *TUR* greater than 4:1, then either gage block calibration source would be acceptable.

TABLE 3. Calibration of 0-25 mm micrometer with gage blocks calibrated by different sources.

Uncertainty Source	Standard Uncertainty (μm)	
	4:1 <i>TUR</i>	2:1 <i>TUR</i>
Gage block tolerance	0.173	0.173
Calibration uncertainty	0.038	0.075
Ambient temperature and the difference in the coefficient of thermal expansion	0.100	0.100
Difference in the temperature	0.125	0.125
Combined and expanded uncertainty using $k=2$	0.478	0.495

The key to doing this type of uncertainty management is to carry the uncertainty of the calibration of the gage block to the subsequent uncertainty analysis of the micrometer calibration. Many uncertainty analysis examples only include the tolerance of the gage blocks and not the uncertainty of the calibration to the tolerance [12]. Instead of applying a guard band that does not consider the measurement application, the uncertainty of the calibration measurement is passed to the subsequent measurement. This approach should always be possible as the uncertainty should be available from the calibration certificate, particularly if the calibration is from an accredited laboratory [3].

This approach to uncertainty management combines the *MPE* of the equipment used in the subsequent measurement with the uncertainty of verifying the *MPE* through a root sum square of their standard uncertainties. The result is an increase in the contribution of the *MPE* to the uncertainty of subsequent measurements based on the *TUR* of the calibration. The results for a few *TUR* values are shown in Table 4. This analysis depends on the assumed distribution of the *MPE*; the results in Table 4 include both the uniform and normal distribution.

TABLE 4. Increase in the contribution of the *MPE* on the uncertainty of the subsequent measurement due to the *TUR* of the calibration.

<i>TUR</i>	Increase in <i>MPE</i> Contribution	
	Uniform	Normal
4	2.3%	3.1%
3	4.1%	5.4%
2	9.0%	11.8%
1.5	15.5%	20.2%
1	32.3%	41.4%
0.5	100.0%	123.6%

While a 4:1 *TUR* may have its history in risk analysis [6], the results in Table 4 show how a *TUR* greater than 4 works in the world of measurement uncertainty. When the *TUR* is greater than 4, the increase of the uncertainty is around 2% to 3% versus considering the *MPE* alone (and assuming a theoretical “zero” uncertainty for verifying it). This slight increase would probably be considered negligible.

While the results in Table 4 are interesting, the real benefit of uncertainty management is results

such as those shown in Table 3. These results can be generalized by analyzing the impact that the *MPE* of measuring equipment has on the uncertainty of the measurement utilizing that equipment. As the contribution of the *MPE* to the measurement uncertainty gets smaller, the influence of the uncertainty of the calibration that verified that *MPE* also decreases.

Figure 1 shows the increased uncertainty of the subsequent measurement as a function of the ratio of the *MPE* to the combined and expanded measurement uncertainty for different *TUR* values (of the original calibration). This is the same as the results in Table 3 but expanded across a variety of cases. Figure 1 can also be used to show a type of “equivalent 4:1 *TUR*”. For example, if the *MPE* is only 10% of the uncertainty, then the uncertainty of the calibration of the *MPE* could be twice the *MPE*, i.e. *TUR* = 0.5, and a 4:1 *TUR* could still be achieved in the subsequent measurement. These results show that risk analysis or uncertainty based decision rules for calibration can be overly conservative depending on the contribution of the calibrated *MPE* to the uncertainty of the subsequent measurement.

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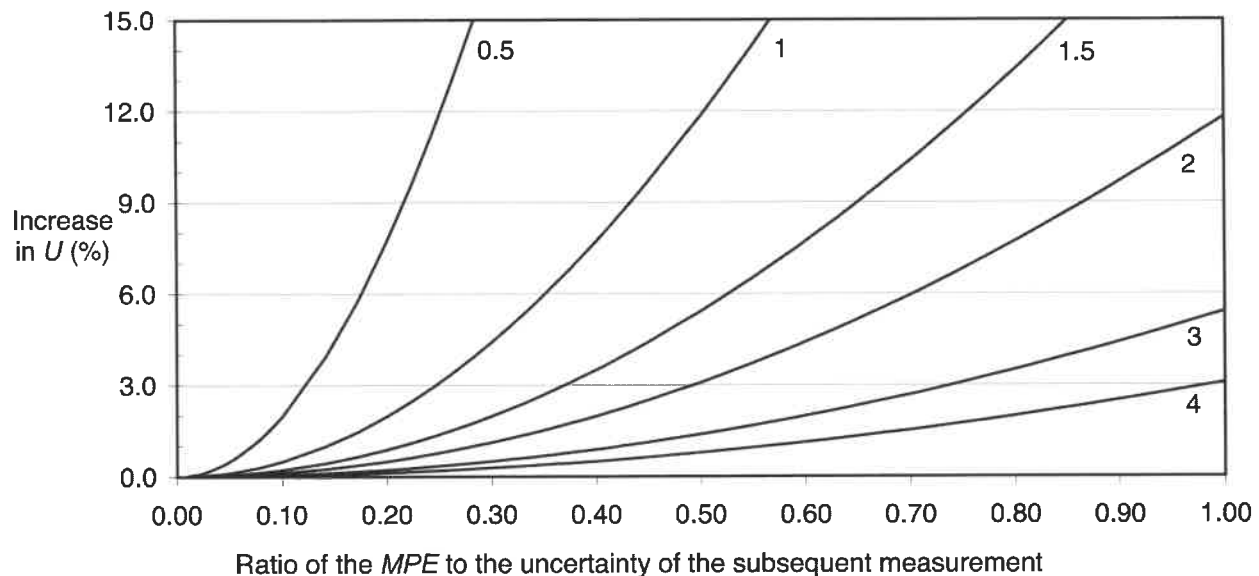


FIGURE 1. Percent increase in the uncertainty of a subsequent measurement versus the ratio of the *MPE* to that uncertainty for different *TUR* values for the preceding calibration of that *MPE*.

ADVANCED GDT ANALYSIS TO FURTHER REDUCE REJECTS AND IMPROVE REWORK TIME & INSTRUCTIONS

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MEANINGFUL GD&T ANALYSIS:

The purpose of this session is to describe the advantages of advanced analysis software when applied to the data collected by coordinate measuring devices.

Coordinate Measuring Devices have become a staple in the quality control industry. However, while the technology and, therefore, the accuracy of these devices have improved dramatically over the years, the ability to analyze the data collected has, with a few exceptions, remained static. This means that with the average analysis capabilities available, CMDs are reduced to being used as Pass/Fail toll gates.

This inspection process then becomes considered "overhead" because it is not contributing anything of substance to the manufacturing process. Some CMDs are used inside a production line supplying data directly to SPC databases. This allows the manufacturing process to be maintained and so, in these cases, the CMD is considered more a production gage rather than "overhead". Even these machines, however, are not performing to their full potential in assisting manufacturing in their efforts to make good parts quickly and inexpensively.

The key advantage to using a CMD can be seen when advanced analysis capabilities are available. With the use of a powerful analysis engine, a CMD transcends the usual good part/bad part use and becomes a valuable aid to manufacturing, rather than being the "bad guy" that fails a part at the end of its manufacturing process. The CMD can become an extremely powerful trouble-shooting tool for the owner of the manufacturing process, and a predictor of potential problems. Even when used as an end inspection device, if the analysis software cannot correctly calculate material or datum bonuses for the applicable tolerances, good

parts may fail inspection. And worse than good parts failing, the bad parts pass. Correct material and datum bonus calculations remain among the most elusive analysis elements for inspection devices.

Another tolerance element that remains largely unsupported is the composite and compound tolerances. There are many opportunities for an inspection to pass a part with patterns of holes only to then have that part fail to assemble. This is an extremely important tolerance type for components that have auxiliary parts attached using bolt patterns. The loss of production is not exposed until assembly where problems start to get very expensive. Time is then lost investigating why a part that passed inspection would not build. In some cases, in an attempt to make the assembly easier, design changes are made that are absolutely unnecessary and inappropriate. Finally the component part is remanufactured and, if the inspection problem was not recognized and rectified, the whole cycle can start again.

When inspecting a surface profile, datum bonus can be critical to the acceptance of the feature being measured. By using full GDT support (ASME and ISO standards), with full control of degrees of freedom applied to the tolerance analysis, suspect components can be analyzed to allow the user to determine if the part really is bad and if it can be saved. An example of the advantages DOF information and manipulation can supply is:

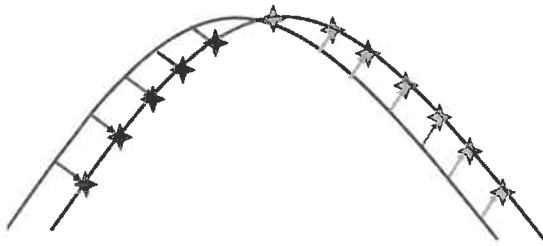


FIGURE 1. Depicts a reasonable simple shape; the blue line represents the nominal and the red and actual shape. In the example shown the actual profile is good but it is in the wrong place. Typical inspection data for this feature would show negative point deviations at the magenta locations and positive deviations at the cyan locations.

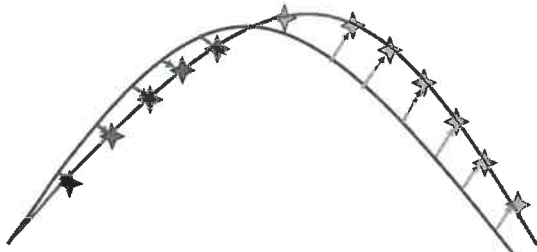


FIGURE 2. In this example the shape is bad. Yet the data supplied would still be negative deviation at the magenta locations and positive deviations at the cyan location.

With an analysis tool that allows DOF manipulation, releasing all the DOFs allows the data to be best fit against the nominal, allowing the shape to be analyzed regardless of position. This would give a pass on the first example yet still fail on the second.

Typical analysis tools will tell you the tolerance failed and will show the points' values. It is not possible to tell which of the described conditions applies without being able to release DOFs and find the best case. Using these analysis methods can save significant amounts of money by preventing scrap and assisting in rework.

In this way the user can work quality into the product instead of checking for it at the end of the manufacturing process.

GD&T is designed to facilitate the manufacture and assembly of component parts. When applied correctly, these analysis tools simulate the mating features and the resulting analysis guarantees that the inspection results affirm or deny the usability of the component. Incorrect drafting and poor analysis cost the manufacturing industry untold amounts of money each year: there is too much actual scrap and too many incorrectly scrapped usable parts. If we apply the tools we have to better investigate and improve the quality of the products we make, the resultant savings and the increased production will be substantial.

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metrologic group leads the way in independent 3D measurement solutions with the most versatile 3D measurement analysis and reporting software available on the market today! metrologic group 3D solutions are in use throughout the world by the largest and most successful cross-industry companies. Whether simple manual measurements, large scale applications, high accuracy or complex GD&T evaluation using point cloud type of data, metrologic has a solution that will finally make your device productive and efficient. Thousands of professionals in a variety of industries such as: automotive, aerospace, agriculture and consumer products have already standardized on our advanced solution and benefit from our new approach to GD&T analysis to deliver always better analyzed parts at any steps of eth manufacturing processes. More information available online at www.metrologicgroup.com or direct any inquiry via phone at 248.504.6200 or at metrologic.usa@metrologicgroup.com.

ISO 10360-2: 2009 – CHANGES AND THEIR RELATIONSHIP TO APPLICATIONS AND TOLERANCES IN INDUSTRY TODAY

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The recent changes to ISO 10360-2 provide a number of additions and clarifications which are driven by emerging applications and the demands placed on coordinate metrology equipment by today's tolerances. This paper will provide an overview of the ISO 10360-2 modifications, and present case study information for current industrial applications.

In recent months, the world economy has experienced abrupt change, which while devastating certain industries, is providing others with opportunity for growth. All the while, the manufacturing industry must evolve to meet the needs of mega-trends like; an aging population, and an environmentally conscious world. Competition, now greater than ever, will continue to drive miniaturization and at the same time contribute further to shrinking tolerances in general, and in specific, on large workpieces.

All this drives the demand for a clearer understanding of measurement uncertainty which in turn drives the needed change to standards like ISO 10360-2. Process control requirements, complex workpiece geometry, advanced materials, advancements in sensors, and the drive towards in-line measurements on

the production floor also play a role.

This paper will introduce the reader to ISO 10360 in general and to new specifications for:

- Repeatability
- Offset Stylus Roll Performance

New Rules for:

- Uni or Bi-directional probing
- Large and Duplex CMM's
- Loading Effects
- Optical Sensors

Details for:

- Environmental Conditions
- Expansion Coefficients
- Disclosure of Test Uncertainty

Application case studies will include examples from Wind Energy, Medical Devices, Aerospace, and other industries. These case studies will help illustrate the need for greater clarity and understanding of measurement uncertainty. They will also serve as a catalyst for open discussion on Coordinate Measurement Machine (CMM) error budgeting in the manufacturing process.

SURFACE TEXTURE MEASUREMENT USING AN OPTICAL METHOD

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1. INTRODUCTION

A flat engineering surface observed under appropriate illumination will exhibit a specific morphology depicted in the form of a pattern of bright and dark (shadow) areas. This recorded optical morphology will be unique for each surface and depend on the type and dimension of surface roughness irregularities. The present study proposes an optical method for surface roughness assessment using Morphological Image Processing (MIP).

Keywords: Surface Texture, Morphological Image Processing.

2. APPLICATION OF MORPHOLOGICAL IMAGE PROCESSING

If the beams of white light are incident on a rough surface, each irregularity will not allow the light beams to illuminate the area behind it, thus, a shadow will appear on the surface as shown in figure 1. It seems that these shadow and bright areas can reflect an indication about surface roughness. This was the starting point of the current research; how to prove analytically that the "shadow width" could be applied to evaluate the surface roughness. References [1] to [8] represent some of the references used in the performed literature review.

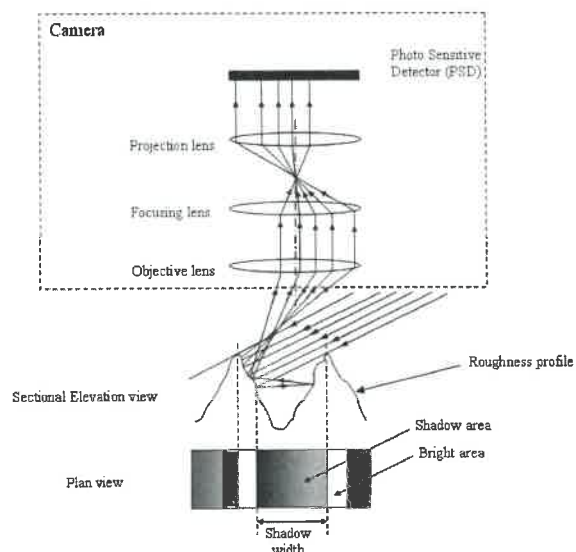


FIGURE 1. Incidence And Reflection Of Light On General Rough Surface (Sectional Elevation View) And The Expected Image Of Surface (Plan View).

In order to illustrate how the shadow width resulting from the illumination of surface roughness at a specific incidence angle is affected by the roughness form and dimensions, a two-dimensional model (Figure 2) is represented by a generalized Fourier Series (FS).

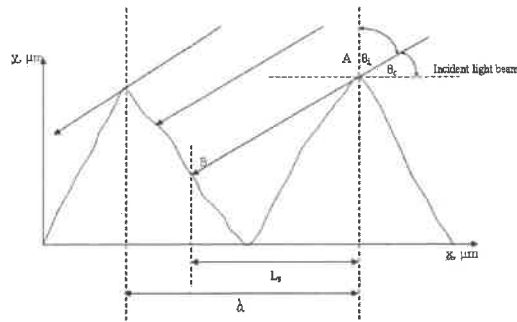


FIGURE 2. Incidence Of Collimated Light Beams On A General Roughness Form.

If the light is incident at an angle “ θ_i ”, a shadow of width “ L_s ” will result.

$$L_s = X_A - X_B \quad \dots\dots\dots (1)$$

The analytical analysis started with the investigation of the ability of the shadow width to distinguish between different assumed roughness forms. Then, the effect of changing the roughness amplitude and wavelength on the resultant shadow width is investigated. At last, the effect of changing the incidence angle on the shadow width was also studied.

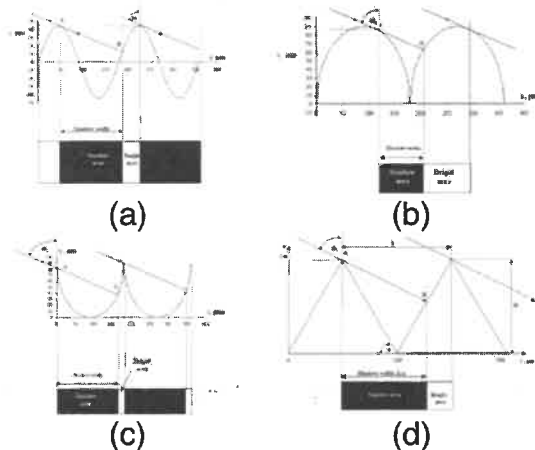


FIGURE 3. Illustration Of A Light Beam Incidence On Assumed Roughness Forms; (A) Sinusoidal, (B) Circular, (C) Inverted Circular, And (D) Triangular.

Based on the analysis results, the shadow width was found to be a reliable parameter that can be used to distinguish between different forms at different conditions.

3. PROPOSED MIP METHOD

The procedure followed in the proposed method is illustrated in figure 4

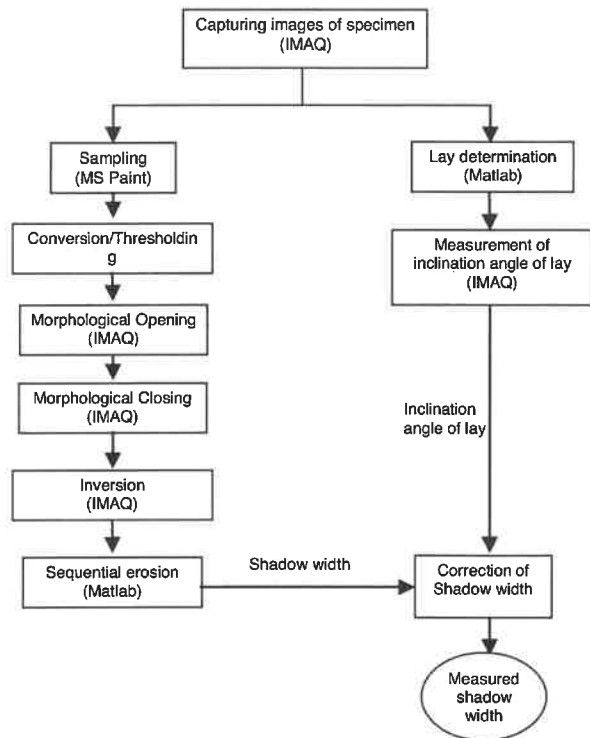


FIGURE 4. The Proposed MIP Method.

Through the proposed method certain morphological processes are applied such as grayscale thresholding, binary opening, binary closing, and binary erosion. These processes will be explained through the following pages.

Grayscale thresholding is to convert grayscale image to a binary image. The available software program “Imaq Vision Builder 6” provides most of the common thresholding techniques. In the current study, the applied thresholding technique is the “entropy” because it is best suited for detecting objects present in small proportions on the image and suitable for default detection. Figure 5 illustrates the effect of “entropy” thresholding on a sample image.

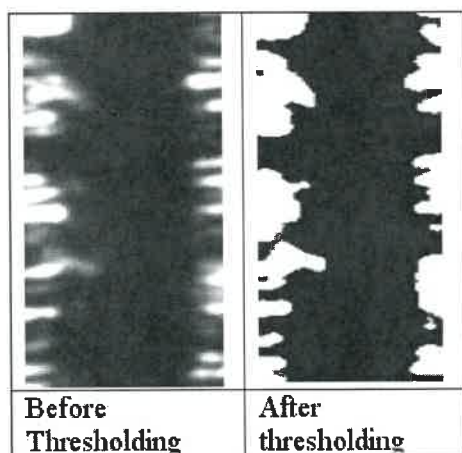


FIGURE 5. The Effect of Thresholding on A Sample Image.

3.2 Binary Morphological Opening:

The opening is morphological erosion followed by dilation. This morphological treatment removes small white particles surrounded by large black backgrounds (salt noise). Figure 6 illustrates the effect of binary opening on a sample image.

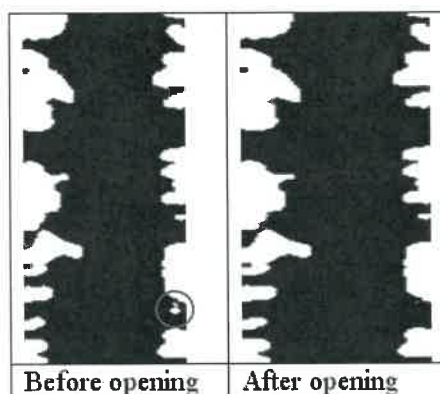


FIGURE 6. Effect of Opening on A Sample Image.

3.3 Binary Morphological Closing:

The closing is a morphological dilation followed by erosion. This morphological treatment removes small black particles surrounded by large white backgrounds (pepper noise). Figure 7 illustrates the effect of binary closing on a sample image.

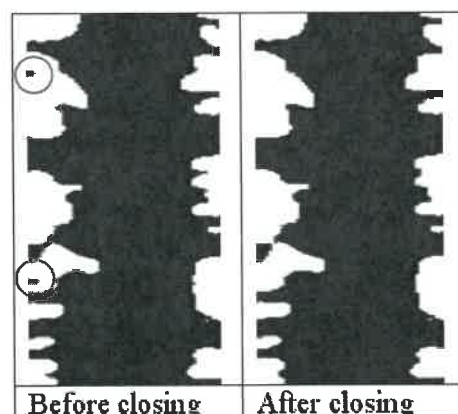
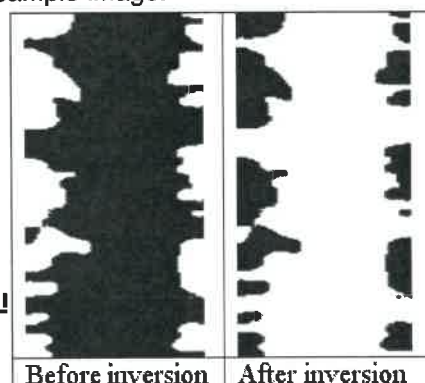


FIGURE 7. The Effect of Closing on A Sample Image.

3.4 Binary Image Inversion:

This process converts the value of each pixel in such a way that the white pixels [level 1] become black pixels [level 0] and vice versa. The target of this process is to convert the shadow areas (black pixels) to be white pixels. Figure 8 illustrates the effect of binary inversion on a sample image.



3.1 GI

FIGURE 8. Effect of Inversion on A Sample Image.

3.5 Sequential Binary Morphological Erosion:

Through this process the developed MATLAB 6.5 software program erodes the inverted image by a square-structuring element. The structuring element's size increases as long as there's still a difference between the eroded and input images. The sequential binary erosion stops when the structuring element can't perform the erosion, thus, there'll not be any difference between the eroded image and the input image. This stoppage happens only when the size of the structuring element just fits into the width of the shadow area. Thus, this size is exactly equal to the shadow width.

4. EXPERIMENTAL WORK

Through the analytical analysis of assumed roughness forms the shadow width showed a

remarkable response to the variation in roughness form, amplitude, wavelength, and incidence angle of light. However, to validate this behavior experimentally actual roughness forms should be examined. To accomplish this nine shaped specimens were produced using different feed rates and tool angles to provide variety in the values of roughness parameters. In the current study, six roughness parameters were measured using calibrated computerized Talysurf2.

4.1 Analytical Analysis of Real Roughness Forms

Cartesian coordinates for one thousand points on real roughness form are needed to determine the appropriate FS. Computerized Talysurf2 satisfies this need by providing not only a graphical presentation of the measured roughness profile but also the Cartesian coordinates of the points on this profile. Figure 9 illustrates an example of the original and the FS profile after eliminating minor harmonic waves for one of the nine specimens.

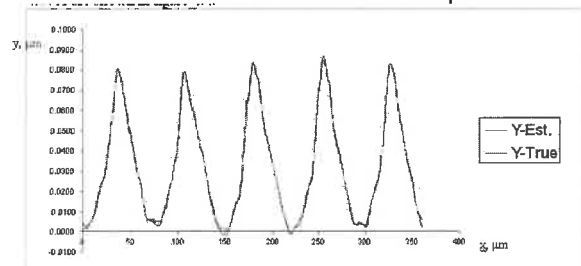


FIGURE 9. Illustration of Initial Profile (Y-True) And Resultant Profile After Eliminating Minor Harmonic Wave (Y-Est.).

4.2 Experimental Set-Up

The preliminary setup applied consists of a black and white camera (Hitachi KP M22-1/2 inch image size- 410,000 pixel/inch² Resolution) ,a white light source (slide projector), and flat surface. Figure 10 illustrates the preliminary setup.

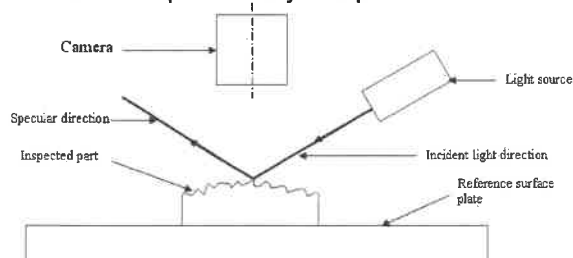


FIGURE 10. Preliminary Experimental Set-Up.

4.3 Sources Of Error

There are three main sources of error that must be considered in order to minimize the measurement cumulative error, they are:

- 1- The parallelism error between the specimen's upper surface and the reference surface plate.
- 2- The perpendicularity error between the optical axis of the camera and the measured surface.
- 3- The angularity error between the incidence light beams and the measured surface.

The considerations applied to reduce the effect of the mentioned sources of error are as follows:

To minimize the parallelism error, a sin table set at the measured inclination angle is used to hold the specimen over the datum surface plate as shown in figure 11.

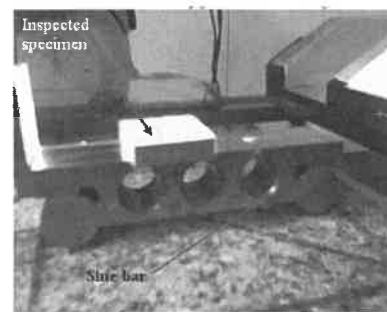


FIGURE 11. Setup Used To Ensure Parallelism Between Surface Of Specimen And Reference Plate.

The optical axis of the camera must be perpendicular on the measured surface in order to determine the correct projected width of the shadow. To minimize the effect of this error the principle of alignment measurement is applied. The hollow and solid cross targets are mounted on two identical vee blocks. The Vee blocks are aligned together using straight edge. A mirror with 45-degree inclination angle with the reference plate is mounted in front of the hollow target. A diffused white light beams pass through the solid and hollow targets. The projected images of the targets incidence on the mirror that reflects them to the camera. Since the mirror is inclined by 45 degree , then the targets will coincide when the optical axis is perpendicular to the reference plate. Figure 12 illustrates the set-up applied for eliminating the perpendicularity error and figure 13 illustrates an image of the actual set-up. Figure 14 illustrates an image of the target capture during the elimination of the perpendicularity error .

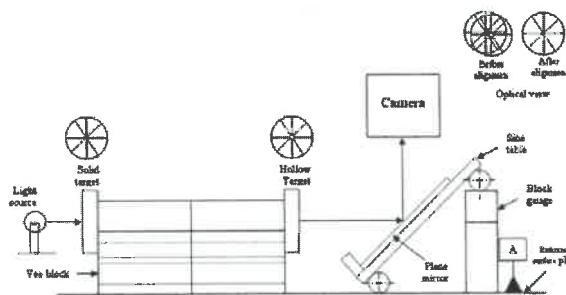


FIGURE 12. Set-Up Applied for Checking Perpendicularity Between The Camera's Optical Axis And The Reference Plate.

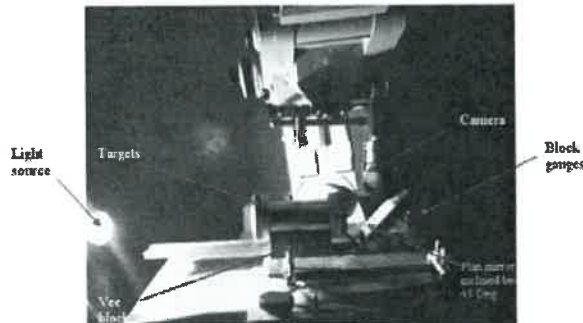


FIGURE 13. Setup Applied To Adjust Perpendicularity Between Optical Axis And Reference Plate.



FIGURE 14. An Image of The Target.

It is important to adjust the incidence light beams at a known angle. Thus sine table and pendulum type spirit levels were used to accomplish this target as illustrated in figures 15 and 16.

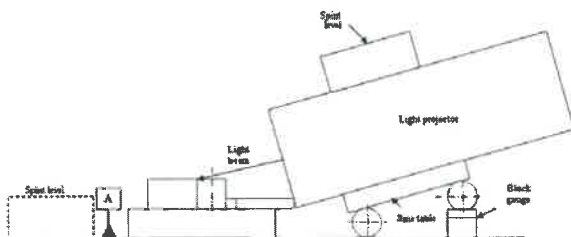


FIGURE 15. Set-Up Applied For Checking The Angle Between The Incidence Light And The Specimens' Surface.

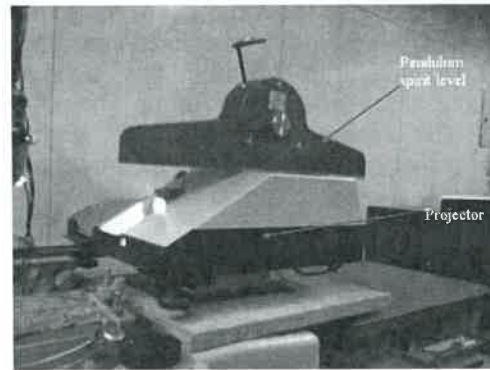


FIGURE 16. Setup Used To Determine The Inclination Angle Of Light.

5. RESULTS of EXPERIMENTS

Using the steps illustrated in the experimental work, a set of nine shaped specimens were imaged and morphologically analyzed to determine the average shadow widths. For each specimen there are ten images, the first five are those captured when the surface was illuminated from the right direction at five different incidence angles and the second five were illuminated from the left. Also, six of the roughness parameters (R_t , R_v , R_p , R_a , R_{Sm} , and R_{da}) were measured for the nine specimens using a computerized Talysurf 2. Figure 17 illustrates the relationship between the average shadow width and R_a .

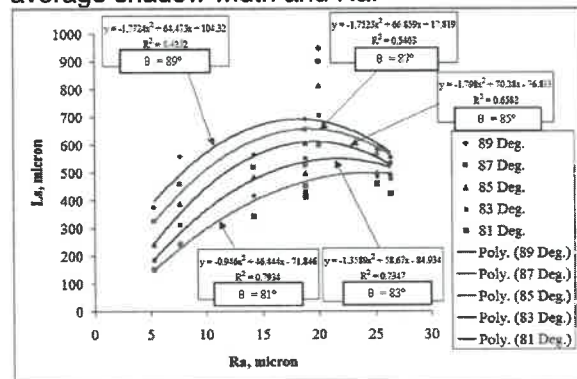


FIGURE 17. Relationship Between Average Shadow Width (L_s) And R_a .

6. PROFILE RECONSTRUCTION

The proposed method could apply one incidence angle to determine any of the considered six roughness parameters using the generalized mathematical models. However, when considering the idea of using five different incidence angles another benefit could be gained. At any incidence angle, the light beam act as a straight line tangent to one point on the peak of roughness form and intersect another

one on the adjacent side of the consecutive roughness profile. This idea looks like a scanning processes (see figures 18 and 19) of one side of the roughness profile, especially, the peak part that is very important for determining the wear, stiffness and friction capabilities of the engineering surfaces.

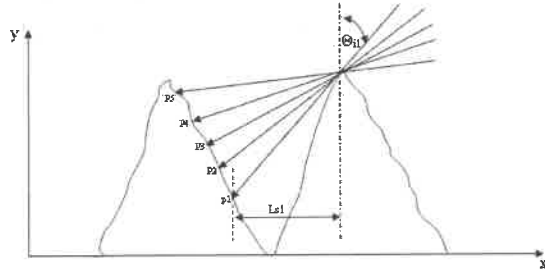


FIGURE 18. Scanning Approach Using Illumination At Different Angles.

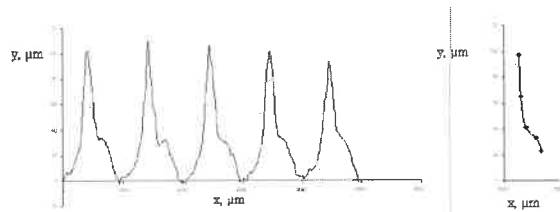


FIGURE 19. Original and Reconstructed Roughness Profiles for A Specimen.

7. CONCLUSION

The shadow width can be used to estimate roughness parameters using morphological image processing. Also, it could be used not only for assessment but also to reconstruct parts of the roughness profile.

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FEATURE UNCERTAINTY CALCULATIONS FOR CMMS

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Overview:

The task of estimating and calculating feature uncertainties can be challenging to the most seasoned metrologist. The task of defining the various errors that comprise the feature calculation requires knowledge of the CMM and its specific errors as well as the methodology of the measurement and evaluation that may be the result of more than one feature measurement. Propagating and estimating these errors can be time consuming as well. In this paper our goal is to introduce methods for comparing and estimating error budgets for different CMMS and a short less rigorous method for comparing the different CMMS relative to selecting the one CMM best suited for the requirements of a specific work piece. Then we have an I++ Simulator that can be used by various software manufacturers to estimate feature uncertainties.

The Short Comparison Method:

We have developed a method for selection of a suitable CMM to measure various features using published specifications from the CMM manufacturers and in our case the various range of our product offerings. We enter the various ISO 10 360 CMM Specifications into an Excel Spreadsheet that has been structured to use these ISO 10 360 values and calculate features of size, form and position. Our spreadsheet permits the entering of more than one CMM type and specification, environmental conditions in order to have an estimated feature uncertainty. We typically pick the tightest tolerances for our calculator in order to save on the time it takes for the selection process. We simply use different color codes for the resultant so we can quick review where our expanded uncertainties lie with respect to the feature tolerance.

We use the following ISO 10 360 values for our calculations:

- ISO 10 360-2 MPE_E Volumetric Length Measuring Error
- ISO 10 360-2 MPE_P Volumetric Probing Error

- ISO 10 360-4 MPE_{THP} Defined Path High Density Scanning Error
- ISO 10 360-5 MPE_{AL} or M_L Multi-Styli Length Measuring Error

Thermal issues:

- Assume homogeneous work piece and its CTE value
- Maximum delta of the machine and part from 20°C

Other factors consider:

- Feature reproducibility
- Datum reproducibility

Once we have entered these values for the various CMMS that we may either have in our facility or to determine an appropriate CMM for selection and purchase we next enter our feature information into our calculator. The calculator is designed in sections for various feature types.

- Distances and diameters
- Position evaluations with single stylus and another section for multi-styli considerations
- Form tolerance features that are probed using single and or multi-styli configurations
- Form tolerance features that are scanned using single and or multi-styli configurations

From these simple inputs one can easily compare various CMM hardware and identify areas of concern as well as to view the impact of thermal affects on the resultant uncertainties. It is understood that this method provides a good evaluation and is not perfect. One should always test and verify the results on the CMM using GR&R methods or a study of standard gage components such as rings, length standards, geometric masters, and various interim CMM test artifacts as well as a means of verifying the CMM has not deteriorated over time.

Our uncertainty model for diameter:

CMM error component is calculated using MPE_E and the feature size.

$$MPEE = 3 + L/400$$

$$\text{Diameter} = 920 + 0.090/-0.000\text{mm}$$

The CMM error component in this example is ± 0.0053 .

We also consider the following errors into our expanded uncertainty:

Feature Repeatability

Datum Repeatability

Thermal issue $10\%CTE \cdot \Delta T$

Using a very simple propagation for the expanded uncertainty we simply take the square root sum of the squares and multiply this by 2 for the coverage factor. Knowing this we simply divide the value into the tolerance and obtain a % of tolerance used by the expanded uncertainty. We break this into 3 different color codes as follows:

No shading <10%

Yellow shading <20% and >10%

Red shading >20%

In this example the material is steel with a CTE of $11.5E-6$ and a ΔT of 2°C , repeatability we left at zero and the expanded uncertainty was 0.0033mm of 14.6% tolerance utilization. If one simply tightens the environment from 2°C to 1°C the expanded uncertainty changes to 0.0031 and 13.9%. It gives the lay person a simple tool to review feature uncertainties.

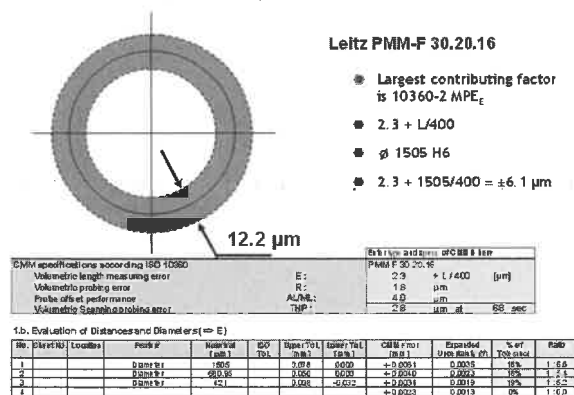


Figure 1: Example of the Hexagon Uncertainty Calculator

During the presentation I will show a few scenarios for everyone and the layout of our uncertainty calculator.

The VCMM virtual CMM:

The uncertainty of measurements made on a CMM is extremely complex and difficult to determine due to the specific CMM geometric error, drift factors, probing system and styli lengths and configurations as well as the environmental impact on the overall system. With this in mind, the German Bureau of Standards PTB developed methods to model the CMM, environment, probing systems for the automatic determination of measurement uncertainties for CMMS using the Monte Carlo simulation.

Zeiss (Calypso Software) and Hexagon Metrology (Quindos Software) have implemented this VCMM into their respective software product offering. For this paper I will only discuss the Hexagon Metrology Product Offering of the Quindos I++ Simulator. The I++ simulator permits all metrology software packages with an I++ interface the ability to use the Quindos I++ simulator, thus the uncertainty calculated by the VCMM includes the host software related algorithm errors into the expanded uncertainty. The use of a simulator has unique advantages since we have non hexagon products as well as our hexagon product offerings modeled into the Quindos7 I++ simulator. The user can simply establish the scenario that satisfies his specific hardware configurations and then run his part specific program through the simulator to obtain feature uncertainties. If a specific site has different CMMS, the user can use the Simulator to test his part in order to utilize the various available CMMS in the most efficient fashion with acceptable uncertainties or to identify a need for a CMM that he may not own. It also will highlight features that may need some alternate gauging methods verses the CMM.

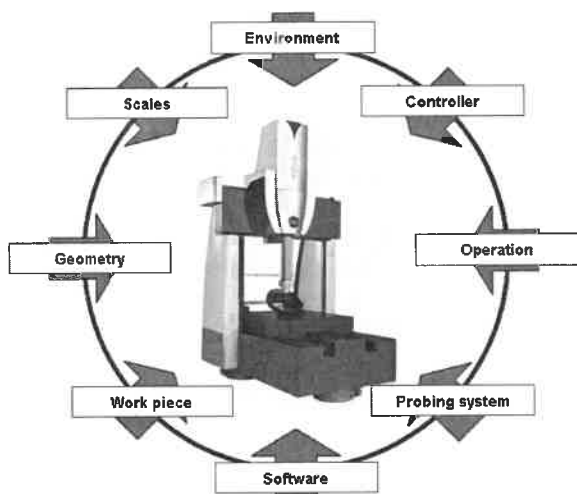


Figure 2: Virtual CMM Uncertainty Contributors

VCMM Uncertainty Contributors:

Figure 2 shows the various uncertainty contributors that are used by the VCMM. The PTB has developed a software product to support the creation of input parameter files and this software product is called VCMMTool. The VCMMTool provides a method for the user to enter the geometric parameters of the CMM, temperature and gradients, as well as material constraints and other constraints. In order to characterize these one must follow some strict rules which I will only briefly summarize:

1. Probe Heads – the PTB has modeled various probing systems and Quindos provides an easy tool and procedure probing points according to a specified pattern and transmitting results to the VCMM database
2. Parameterization of the CMM is done by measuring a calibrated sphere or hole plate in a minimum of 4 predefined orientation or 6 positions for a complete map and this information is transmitted back to the VCMM database.
3. Environmental errors are determined by long term monitoring of temperature and gradients using a multi-channel data logging system. These values are used to estimate the thermal bending of the CMM as well as influences on the test part.
4. CMM drift is achieved by measuring a sphere every 30 minutes while excising the CMM during the dwell time.

5. Stylus modeling by measuring a specified point pattern for the different tips that are used for the part measuring
6. Influence of surface roughness on the feature measurement is done using flatness standards

Knowing the various errors for a specific CMM permit a user to connect to the Simulator via their specific metrology software with a I++ interface and create the scenarios that make sense from their perspective, not ours. Figure 3 shows the data flow graphically.

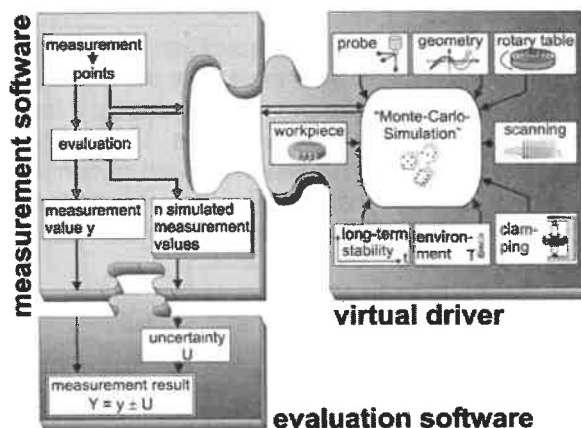


Figure 3: VCMM Data Flow

The process is now quite simple once the measurement program is written and assuming the various CMM systems have been quantified. Theoretical points are sent from the host software via the I++ simulator to the VCMM which takes into the various CMM geometric and thermal errors, probe specific as well as the probing strategy sending back to the host points that have been processed in the VCMM model with random errors based on the kinematic structures and associated errors as mentioned previously. This process is repeated many times until a stable standard deviation has been reached.

The following figure 4 graphical shows the process and errors incorporated in this approach.

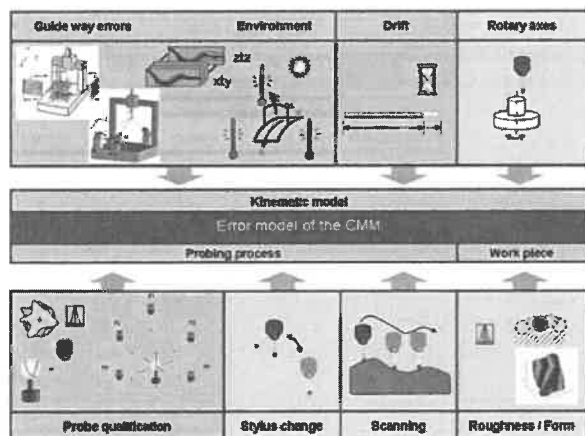


Figure 4: VCMM Process

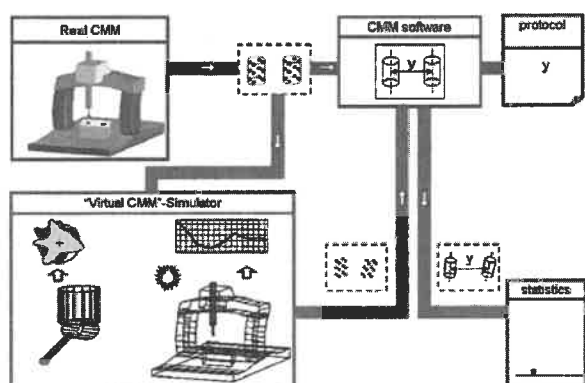


Figure 5: 1st run of the part program [1]

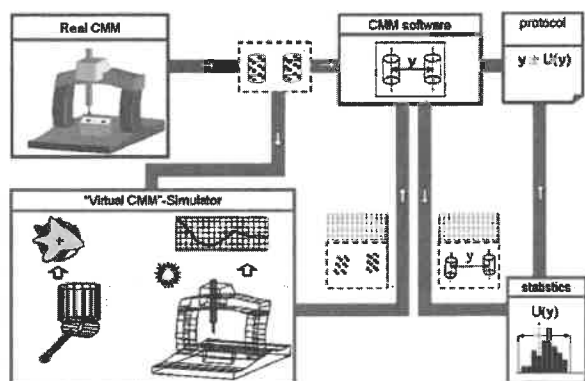


Figure 6: n^{th} run of the part program

The part program is ran multiple times in the simulator and the host software via statistics is used to calculate the resultant standard deviation which is typically multiplied by 2 for its coverage factor. A coverage factor of 2 provides the equivalent of 95% that all measurements will be within this range.

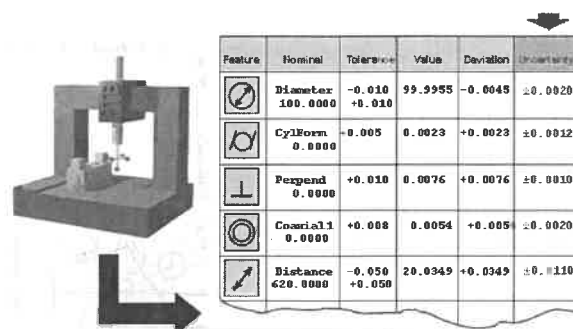


Figure 7: The results

Conclusions:

It is quite clear that there are required efforts by individuals to calculate feature uncertainties and highly skilled individuals can systematically prepare a list of errors and place a standard deviation for each according to the rules of GUM. The use of the Simulator and the VCMM permits a more rigorous approach that dose not requires the same high expertise and incorporates the metrology program into the process. It does take some effort to quantify these errors, but once done it only requires monitoring to make sure the condition of the system is still valid, but one should do this take regardless to verify the CMM has not changed over time.

Currently work is being done for the implementation of the rotary axis into the VCMM and for horizontal arms. We are working on our simulator to include the OCVCMM from the PTB which is scheduled for 2010. Currently we have our older VIM driver implemented into our simulator and the determination to use the simplistic model or the more comprehensive model from the PTB is a registry setting in our software and one would need the PTB software as well.

The Hexagon Feature Uncertainty Calculator provides a simplistic approach to estimating feature uncertainties and may in some cases over state the value, but we also adhere to the philosophy of testing and using a GR&R as a verification method. One could improve our uncertainty calculator by using GR&R methods and then review the two results. Modifications can be made with documented proof.

Measurement without an understanding of the uncertainty makes it impossible to have correlation with other CMMS and or processes.

References:

[1] Michael Trenk (FEINMESS GmbH&Co. KG),
Matthias Franke (Physikalisch-Technische
Bundesanstalt), Dr. Heinrich Schwenke
(Department Coordinate Metrology, 38116
Braunschweig, Germany) The "Virtual CMM" a
software tool for uncertainty evaluation –
practical application in an accredited calibration
lab

GOT A COST PROBLEM? FIX QUALITY!

Dean E. Beutel
Caterpillar Inc., Mossville, IL 61552

Caterpillar is competing from a U.S. base in a high velocity world wide marketplace. This presentation focuses on the business impact of quality. Also, the importance of having a balanced portfolio of Quality Costs will be discussed.

A balanced portfolio of quality assurance programs that address quality costs work together to optimize the whole. Data indicates that these costs can approach 30% of the cost of operations. An improperly balanced portfolio of quality investments may drive too much cost in one area, and insufficient investment in another - suboptimizing overall results.

The key to ensuring a comprehensive balanced approach to quality is the existence and

leverage of a Quality Management System. The QMS at Caterpillar requires a suite of inter related quality focused programs covering all aspects of the business - product design, manufacturing and product support.

The Quality cost portfolio at Caterpillar is well over \$5B – the opportunity is to balance the investment in quality, and then work to optimize it where it makes sense.

Change is tough – and tough times require change. We at Caterpillar are fiercely dedicated to drive change, improve our products, margins, and ultimately the satisfaction of our customers and stockholders.

UNCERTAINTY ANALYSIS OF A SIMPLE FRINGE PROJECTION SYSTEM

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INTRODUCTION

The "holy grail" in durable goods manufacturing is elimination of the need for off-line part inspection. Fringe projection [1-4] is an attractive process for on-machine metrology because the flexibility of the setup and the relative long working distances of the system's components help address several of the challenges associated with on-machine metrology. Specifically, the system components can remain on the machine throughout the machining process and can measure the entire part without machine movement. These help de-couple the uncertainty in the machine tool from the uncertainty in the measurement process.

Literature review on fringe projection indicates a thorough uncertainty analysis is absent. The current work addresses this need, discussing the challenges encountered in the analysis. The results provide much more than just a standard uncertainty value for the current on-machine setup at the National Institute of Standards and Technology (NIST). Rather, the uncertainty analysis serves as a tool to improve several aspects of the process, most notably the calibration process.

MATHEMATICAL FOUNDATION

Fringe projection belongs to the field of stereophotogrammetry, which uses two-dimensional data from multiple coordinate systems to obtain results with an added dimension in a target coordinate system. Two or more two-dimensional camera images from different perspectives of the same real-world scene have correspondence points allowing determination, through solution of the stereo correspondence problem, of three-dimensional coordinates of the surface in the captured scene [5]. Fringe projection allows automated determination of correspondence points by replacing one of the cameras with a projector that projects a known pattern onto the scene.

Thus, in a typical fringe projection system, two-dimensional data from the camera and projector coordinate frames provide three-dimensional data in the real-world coordinate frame. However, to ease analysis and understanding, the current study examines a simpler system with one-dimensional camera and projector data and two-dimensional real-world data.

Points in one coordinate frame can be expressed in another coordinate frame through homogeneous transformation matrices:

$$\begin{bmatrix} hx_c \\ h \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \end{bmatrix} \begin{bmatrix} x_R \\ z_R \\ 1 \end{bmatrix} \quad (1a)$$

$$\begin{bmatrix} wx_p \\ w \end{bmatrix} = \begin{bmatrix} P_{11} & P_{12} & P_{13} \\ P_{21} & P_{22} & P_{23} \end{bmatrix} \begin{bmatrix} x_R \\ z_R \\ 1 \end{bmatrix} \quad (1b)$$

where x_R and z_R are coordinates in the real-world coordinate frame, x_c and x_p are the x-coordinates in the camera and projector coordinate frames, respectively, and h and w are scale factors. C_{ij} and P_{ij} are transformation matrix components expressing real-world coordinates in the camera and projector coordinate frames. Expanding and rearranging Eqs. (1), we obtain:

$$C_{11}x_R + C_{12}z_R + C_{13} - C_{21}x_Rx_c - C_{22}z_Rx_c - C_{23}x_c = 0 \quad (2a)$$

$$P_{11}x_R + P_{12}z_R + P_{13} - P_{21}x_Rx_p - P_{22}z_Rx_p - P_{23}x_p = 0 \quad (2b)$$

Notice that if x_c , x_p , C_{ij} , and P_{ij} are known, there are two equations to solve for the two unknowns x_R and z_R . The equations can be rearranged into matrix form to reflect this:

$$\begin{bmatrix} C_{11} - C_{21}x_c & C_{12} - C_{22}x_c \\ P_{11} - P_{21}x_p & P_{12} - P_{22}x_p \end{bmatrix} \begin{bmatrix} x_R \\ z_R \end{bmatrix} = \begin{bmatrix} C_{23}x_c - C_{13} \\ P_{23}x_p - P_{13} \end{bmatrix} \quad (3)$$

Thus, the output quantities of x_R and z_R depend on the input quantities x_c , x_p , C_{ij} and P_{ij} . Uncertainties in the output quantities are

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functions of the uncertainties in the input quantities [6]. C_{ij} and P_{ij} are determined through a prior calibration.

CALIBRATION

When the fringe projection system is first setup, the camera and projector transformation matrix components are unknown. These components can be estimated using a calibration artifact with known real-world coordinates. The discussion below concentrates on the camera calibration, but can also be applied to the projector.

Examining Eq. 2a, one can see that there are 6 unknown C_{ij} . Because the $[C_{ij}]$ matrix is a homogenous transformation matrix, C_{23} is set equal to 1 for a unique solution. Thus, at least five real-world coordinates and the corresponding camera coordinates must be known to estimate the unknown C_{ij} .

If there are $N > 5$ known non-collinear real-world coordinates, then C_{ij} can be estimated by a least-squares method. N known real-world coordinates yield N equations similar to Eq. (2a):

$$\begin{bmatrix} x_{a_1} & z_{a_1} & 1 & -x_{a_1}x_{c_1} & -z_{a_1}x_{c_1} \\ x_{a_2} & z_{a_2} & 1 & -x_{a_2}x_{c_2} & -z_{a_2}x_{c_2} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x_{a_n} & z_{a_n} & 1 & -x_{a_n}x_{c_n} & -z_{a_n}x_{c_n} \end{bmatrix} \begin{bmatrix} C_{11} \\ C_{12} \\ C_{13} \\ C_{21} \\ C_{22} \end{bmatrix} = \begin{bmatrix} x_{c_1} \\ x_{c_2} \\ \vdots \\ x_{c_n} \end{bmatrix} \quad (4)$$

where x_{a_i} and z_{a_i} are known calibration artifact coordinates. Notice that Eq. (4) takes the form $AC = y$. This means least squares estimates for C can be found by solving the normal equations:

$$C = (A^T A)^{-1} A^T y \quad (5)$$

Note that equations similar to Eqs. (4) and (5) exist for the projector and its P_{ij} values.

DIFFICULTIES WITH UNCERTAINTY

Though estimates for the transformation matrix components follow the above well-known approach, determination of the uncertainties in those components is not so straightforward. Ordinarily the standard uncertainties in fit values are determined by calculating the components' covariance matrix. However, this approach to uncertainty determination assumes all the uncertainty comes from the y vector and the A matrix is known exactly.

In this case, there is also uncertainty in the components of the A matrix. Specifically, the standard uncertainties in the known real-world

coordinates on the artifact come from a calibration certificate for the artifact (type B uncertainty). The standard uncertainty in the camera coordinates come from a statistical analysis of the edge detection process (type A uncertainty). Additionally, when determining the combined standard uncertainty $u(x_R)$, there will be significant correlation between $u(C_{ij})$ and $u(x_c)$ that may be difficult to determine.

To avoid these issues, C_{ij} are left in equation form, so that x_R and z_R are explicit functions of all calibration values and part measurements. However, due to the complexity of the equations, the only way to express them is with mathematical software capable of symbolic manipulation.

ANALYSIS

After substituting the equations for C_{ij} and P_{ij} into Eq. (3), the output quantities x_R and z_R depend only on camera coordinates x_c , projector coordinates x_p , and calibration artifact coordinates x_a and z_a as input quantities. Of note is that these input quantities are all independent. Thus, as defined by reference [6], the combined standard uncertainty in the x-coordinate is:

$$u(x_R) = \left[\sum \left(\frac{\partial x_R}{\partial x_i} \right)^2 u^2(x_i) \right]^{1/2} \quad (6)$$

where $\partial x_R / \partial x_i$ is the sensitivity coefficient for each input quantity, and $u(x_i)$ are standard uncertainty values for the input quantities.

Mathematical software is capable of determining all sensitivity coefficients symbolically:

$$u(x_R) = \left\{ \left(\frac{L_c}{l_c} \right)^2 \left[(V_{x_c} u(x_c))^2 + (V_{x_c}^{cal} u(x_c))^2 \right] + \left(\frac{L_p}{l_p} \right)^2 \left[(V_{x_p} u(x_p))^2 + (V_{x_p}^{cal} u(x_p))^2 \right] + (V_{x_R}^{cal} u(x_a))^2 + (V_{z_R}^{cal} u(z_a))^2 \right\}^{1/2} \quad (7a)$$

$$u(z_R) = \left\{ \left(\frac{L_c}{l_c} \right)^2 \left[(W_{x_c} u(x_c))^2 + (W_{x_c}^{cal} u(x_c))^2 \right] + \left(\frac{L_p}{l_p} \right)^2 \left[(W_{x_p} u(x_p))^2 + (W_{x_p}^{cal} u(x_p))^2 \right] + (W_{z_R}^{cal} u(x_a))^2 + (W_{z_R}^{cal} u(z_a))^2 \right\}^{1/2} \quad (7b)$$

where $u(x_c)$ and $u(x_p)$ are the standard uncertainties in camera and projector coordinates, and $u(x_a)$ and $u(z_a)$ are the standard uncertainties in the known points on the calibration artifact. The non-dimensional sensitivity coefficients (V_i and W_i) are complicated functions of camera, projector, and calibration artifact coordinates. Additionally, the sensitivity coefficients have been separated into those depending on the calibration artifact (superscript "cal") and those with no dependence on calibration (no superscript). This was done to ease calculations but also to aid understanding of the importance of the calibration to the combined standard uncertainty. L_c , l_c , L_p , and l_p are distances relative to the focal points of the camera and projector (see Fig. 1).

RESULTS

To evaluate the sensitivities, values specific to the geometry of the NIST system (see Fig. 2) were substituted into the equations for the sensitivity coefficients. The calibration artifact had uniform spacing of the known coordinates at two distinct heights (see Fig. 3). The results showed that the sensitivities vary with position on the workpiece, meaning different values of x_R and z_R have different sensitivities. However, because the workpiece height is very small compared to the camera and projector working distances, $z_R \approx 0$. Different values of x_R , however, remain significant. Figure 4 shows sensitivities across the workpiece. All sensitivities are rather uniform toward the center of the workpiece, but the sensitivities dependent on the calibration increase near the edges of the workpiece.

With the sensitivity coefficients evaluated, standard uncertainty values were substituted into Eqs. (7), yielding the combined standard uncertainties in the output quantities. The type B standard uncertainty in calibration artifact coordinates ($u(x_a)$ and $u(z_a)$) was assumed to equal $15\text{ }\mu\text{m}$. The type A standard uncertainty in camera coordinates ($u(x_c)$) was $2\text{ }\mu\text{m}$. The uncertainty in projector coordinates ($u(x_p)$) comes from the projector resolution. Therefore, it is a type B uncertainty dependant on the size of one projector pixel. For the current projector, this standard uncertainty was $6\text{ }\mu\text{m}$. The resulting combined standard uncertainties are $u(x_R) \approx 10\text{ }\mu\text{m}$ and $u(z_R) \approx 16\text{ }\mu\text{m}$ near the center of the workpiece. Since the sensitivity coefficients increase toward the edges of the part, standard uncertainties also increase toward the edges (see Fig. 5).

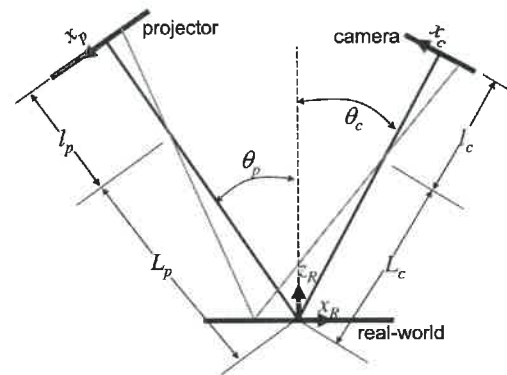


FIGURE 1. Schematic of fringe projection system analyzed in this study. Pinhole models describe both the camera and projector.

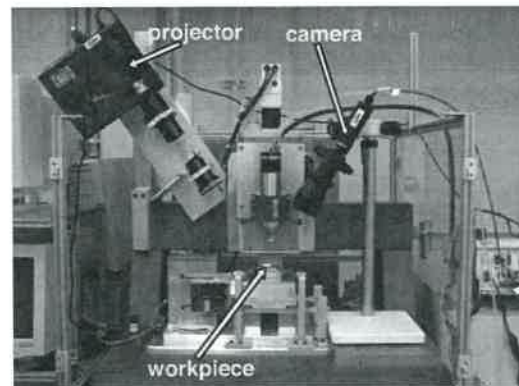


FIGURE 2. Photo of the on-machine fringe projection setup at NIST. For this setup, $L_c = 350\text{ mm}$, $l_c = 66\text{ mm}$, $L_p = 425\text{ mm}$, $l_p = 215\text{ mm}$, $\theta_c = 0.53\text{ rad}$, and $\theta_p = 0.60\text{ rad}$.

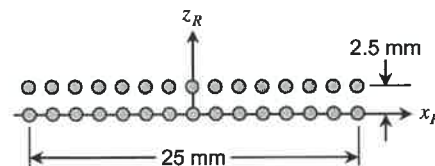


FIGURE 3. Model of a calibration artifact with 30 known coordinates.

LOOKING FORWARD

The uncertainty analysis can provide a useful tool to help improve the current fringe projection system. Because the uncertainty analysis reveals the importance of calibration to the combined standard uncertainty, the calibration artifact can be redesigned and evaluated. For example, redistributing the 30 known calibration points toward the workpiece edges, as shown in Fig. 6, slightly reduces sensitivities near the edges compared to those in Fig. 4(a), but at the expense of larger sensitivities near the center of the part. As such, a calibration artifact with more

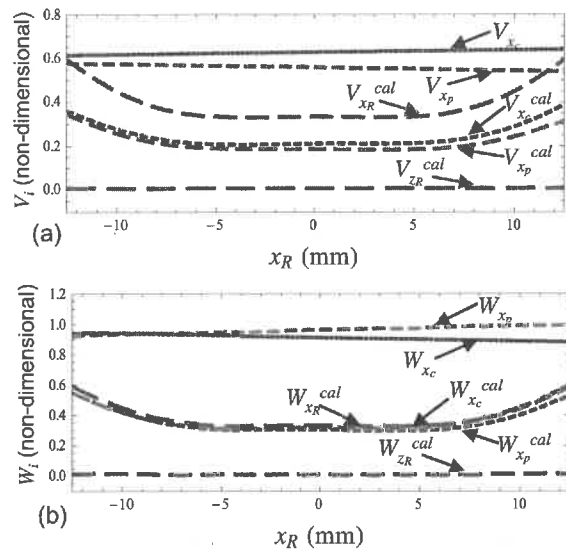


FIGURE 4. Plots of how sensitivities vary with workpiece position. a) V_i and b) W_i .

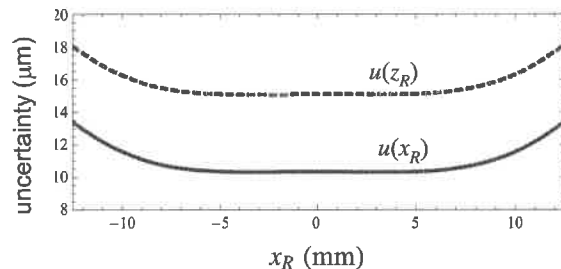


FIGURE 5. Variation of combined standard uncertainty in real-world coordinates with position on the workpiece.

than 30 known coordinates, and a higher density of known coordinates near the edges of the part might be ideal.

When the current analysis is expanded to three output dimensions, y-coordinates will be added to the camera, projector, and real-world. Also, in addition to the rotation about the y-axis already accounted for (θ in Fig. 1), rotations about the modified x- and z-axes will be included. The main concern with expansion is the added computational costs. Changes may be needed in the programming approach made to alleviate excessively long computation times.

CONCLUSION

We have conducted an uncertainty analysis of a simple fringe projection setup. This uncertainty analysis presented an interesting challenge in determining uncertainty due to the calibration process. To address this problem and to ensure

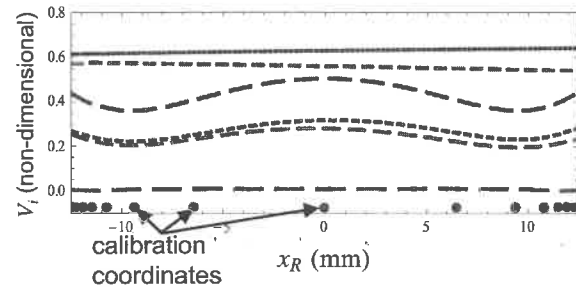


FIGURE 6. Variation of sensitivities with position on the workpiece resulting from re-distribution of the 30 calibration coordinates (blue dots).

all input quantities were independent, transformation matrix components were left in equation form and substituted into the measurement equation. In the end, the sensitivity coefficients, and therefore the combined standard uncertainties, were found to vary with position on the workpiece. The combined standard uncertainties in the output quantities $u(x_R)$ and $u(z_R)$ range from 10 μm to 18 μm .

ACKNOWLEDGEMENT

The authors would like to thank William Guthrie of the NIST Statistical Engineering Division for the insightful discussions regarding the current uncertainty analysis.

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INNOVATIVE MACHINE FREEFORM VOLUMETRIC ERROR MAPPING AND COMPENSATION (VEC) USING A LASER TRACKER

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The need for increased accuracy of large parts for aircraft, heavy machine, shipyard, automobile and energy industries led to the requirement of closer tolerances in machining. Maintaining accuracies of shape and feature locations on these large parts presents unique manufacturing challenges.

Volumetric Error Mapping and Compensation (VEC) using a laser tracker is an innovative method with the potential to improve the best positioning capabilities of today's large machine tools. Prior development work has shown the potential but is complex, time-consuming, laborious, and requires highly-skilled metrology experts. API's latest VEC development calls for the use of a compact Laser Tracker (LT) and an Active Target (AT) to map a CNC machine. Results have shown that the technique is capable of mapping a 5- or 6-axis machine in a matter of 2 hours and yielding a 3x to 4x accuracy improvement.

Prior to the mapping, the machine model is entered into the API advanced VEC software. The software then generates the random poses of the machine tool path and performs a simulated "collision avoidance"

analysis. With a single set-up of the LT within the machine volume and the AT mounted on the ram, the LT tracks and measures the AT positions while the machine moves randomly throughout its entire working volume. Once completed, the VEC software automatically processes the data, generates the error compensation model and graphically displays the machine error. All are done in a matter of minutes. The error compensation model is then uploaded to the Siemens controller where the multi-axis compensation is implemented in real-time.

Since the entire working volume is mapped without limitation of the number of machine axes in merely a couple of hours, this technique makes mapping and improving the machine accuracy more effective and affordable compared to many conventional techniques. This development is conducted in cooperation with Boeing, MAG, Siemens and is partly funded by the NCMS and its affiliates. The modeling technique, the comparison with the conventional techniques and the results of the tests will be presented.

Machine Tool and Motion Error Standardized Definitions for Simplified Error Modeling

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ABSTRACT

Error models for the purposes of understanding and correcting machine motion errors have been used for many years. Most of these models have been developed to define and improve the behavior of specific laboratory devices or commercial products. The adaptation of Error Modeling for general use in factory applications requires the incorporation of a wide variety of machine configurations. Some of these machines and their errors are described in ISO and ANSI Standards.

Limitations of the current number of machine configurations defined in these Standards reduce the effective application of standardization when new configurations are developed. Also, the measurement of a machine is often limited to a few errors by the instrumentation available. This paper proposes more generalized methods for naming machines and their errors, as well as error sign

conventions, to permit a wider application of models. These generalized methods also facilitate communication of the wide variety of error measurements necessary for comprehensive diagnostics and corrections. The research funding to create these conventions has been provided to Independent Quality Labs, Inc. (IQL) by the US Army Research Laboratories in Aberdeen, MD.

1.0 MACHINE CLASSES AND SUBCLASSES

Machine Classes have been defined in the Draft Standard ASME B5.59 [1] as: Turning Machine, NC Turning Machine, Turning Center, Milling Machine, NC Milling Machine, and Milling Center. Machine kinematic arrangements (axis stacking) have been defined in ANSI/ASME B5.54 [2] and a variety of machine-specific ISO Standards.

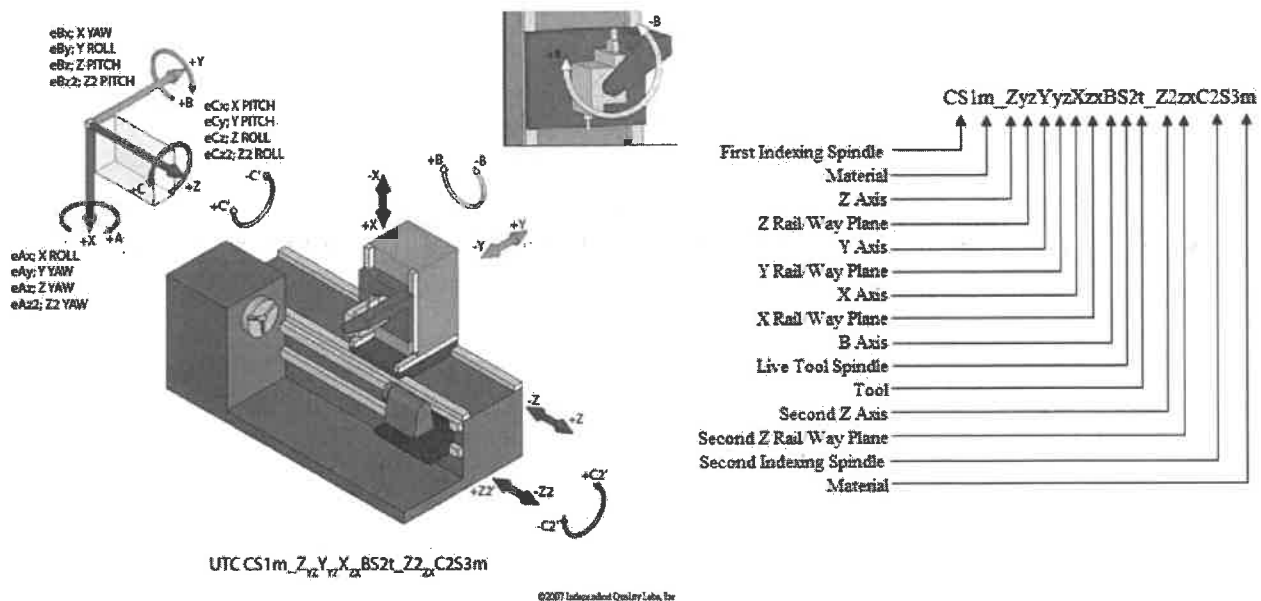


Figure 1: Universal Turning Center.

1.1 Machine classes

IQL has simplified these definitions by adopting machine classifications according to function and orientation of material and/or material working device (tool). Classifications include Vertical, Horizontal and Universal Machining Centers, Turning Centers, Grinding Centers and Welding Centers. The classifications for Machine and NC have been dropped to simplify the list. The term "Centers" is used for all classes since the majority of machines which have been modeled include some type of automatic part loading, tool or part position sensor. Additional Classes can easily be added as other working devices are developed.

1.2 Machine sub-classes

The identification of machine errors requires a complete definition of the kinematic arrangement of machine motion axes. In order to accommodate the classification for Universal Turning Centers, where the material is transferred from one Work Spindle to another, the previous IQL method [3] that defined arrangements from the material to the tool, was abandoned. Upon suggestion from Dr. Thomas Charlton, the proposed IQL approach defines kinematic chains (axis stack) working from a fixed point on the earth through multiple chains to the material and/or the tool. The Draft Standard ASME B5.59 [1] Roll, Pitch and Yaw definitions for Angular Errors required the definition of the Axis Rail or Way Plane to fully describe the error. The resulting proposed Machine Sub-Class definitions start at the earth and proceed upward to the material or tool, describing the plane of the ways, for each kinematic chain (axis stack). Axes with no apparent Way Plane are defined using the Way Plane of the preceding Axis. The simplest example is the Sub-Class definition for the Vertical Machining Center with a Moving Gantry. The more complicated example, which prompted the revision in definitions, is the Universal Turning Center (Figure 1).

2.0 MACHINE ERROR DEFINITIONS

Machine Errors have many properties including motion axes, error source, method of analysis, direction, and sign. To accommodate these properties, IQL has developed the following terminology:

2.1 Parametric Error Names (PENs)

Errors are defined by Test Classes and Test Properties in the Draft Standard ASME B5.59-2

[1]. Tests Classes such as Axis Acceleration, Angular, Motion, and Positioning, and Test Properties such as Circular, Line and Point Tests are considered. The ISO Draft 230-1.5 [4] defines Linear, Positional and Angular deviations using these terms:

For Linear Axes Motion:

EXZ: Linear Deviation	EAZ: Pitch Angular Deviation
EYZ: Linear Deviation	EBZ: Yaw Angular Deviation
EZZ: Linear Deviation	ECZ: Roll Angular Deviation

For Angular Axes Motion:

EXC: Radial Error	EAC: Tilt Error
EYC: Radial Error	EBC: Tilt Error
EZC: Axial Error	ECC: Positioning Deviation

The methods of naming errors provided by these Standards are inadequate to clearly describe all the errors present in a comprehensive model of machine performance. IQL has developed and successfully utilized Locus™ PEN definitions of Machine Errors to describe a large number of Quasi-static, Thermal and Dynamic Errors in machines by extending and modifying the ISO Draft 230-1.5 [4] definitions. Locus™ PEN definitions use a combination of error description, direction and motion axis (axes) terms as follows:

Error Prefix Characters:

Error Types - considering Class, Properties and Method of Analysis

- e – Bandwidth of the Bi-directional Averages
- eb – Average Reversal Error
- ebs – Dynamic Step Reversal
- ei – Dynamic Interpolation Error
- el – Location Error
- ep – Periodic Error
- er – Calculated Repeatability
- es – Dynamic Step Error
- et – Motion Axis Thermal Drift
- etve – Environmental Thermal Drift

Direction Characters:

Error Direction - using the Part Coordinate System, eX, eY and eZ – Indicate the directions of linear displacement errors such as Linear Displacement Accuracy, Straightness, and Spindle Radial and Axial Average Errors. eA, eB and eC – Indicate the directions of angular errors Roll, Pitch and Yaw, Angular Displacement Accuracy, Squareness, Parallelism and Spindle Tilt. A, B and C represent the directions of the errors.

Note: Roll is defined as rotation about the linear guide, Yaw is rotation about an axis in the plane of the linear guide and Pitch is rotation about an axis perpendicular to the plane of the linear guide.

Motion Characters:

Motion Axes - using the ISO-841 [5] Axis Standard and Locus™ PEN Spindle definitions
Linear Axes: X, Y, and Z, with parallel linear axes U, V and W. Machines with many parallel axes the definitions may be indexed by adding a number to the letter (e.g. X1, X2...).
Rotary Axes: A, B and C parallel to X, Y and Z, with additional parallel rotary axes D and E. Machines with many parallel rotary axes may also be indexed by adding a number to the letter (e.g. A1, A2...).
Spindle Axes: S, S1, S2, etc., generally parallel to Z or a, b, or c for the angular direction in which they rotate (e.g. S1a, S2b...).
Turret or Indexing Axes: I, I1, I2 etc., with a subscript a, b, or c for the angular direction in which they rotate (e.g. Ia, Ib...).

2.2 Machine error descriptions

Using the error and motion axis definitions from above, Machine Errors can now be defined as: eXx, eXy, eXz, etc. – Indicating that a single axis is moving to produce the error in the direction of motion.

eAyz, eBzx, eCxy – Indicating that two axes are moving to produce the error. It is important to note the order of the motion axes to assure that the sign of Squareness and Parallelism Errors meet the criteria for the Plus direction (greater than 90 degrees) defined in the ISO Draft 230-1.5 [4] methods. This requires the proper utilization of Primary, Secondary and Tertiary plane and axis designations as shown in Figure 2.

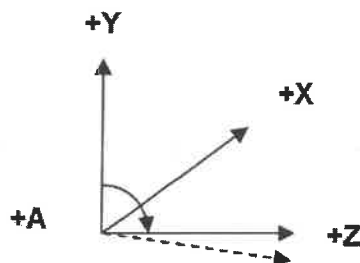


Figure 2: eAyz Squareness.

Other multi-axis Locus™ PENs include:

Parallelism between;

two linear axes

eAzw – Parallelism

eBzw – Parallelism

linear and rotary axes

eAzc – Parallelism

eBzc – Parallelism

Squareness between; Parallelism between;

linear and rotary axes

eAyc – Squareness

eBxc – Squareness

two rotary axes

eAc1c2 – Parallelism

eBc1c2 – Parallelism

Squareness between two rotary axes

eAbc – Squareness

eBca – Squareness

2.3 Machine error sign conventions

Sign conventions for axes motion has been established by ISO 841 [5] using the Right Hand Rule. The conventions are based on the need to create machine motion programs which place the Tool in relation to the Part (Material), regardless of the kinematic arrangement of machine motion axes (See 1.2 above). Locus™ PEN sign convention uses the same logic to simplify diagnosis of Part Errors regardless of the machine arrangement. This rule is also consistent with the current ISO Draft 230-1.5 [4]. The sign of Error Data taken on machines where the part is carried by one or more motion axes is reversed from the direction of the motion axis which is designated with a prime ('). Figure 3 illustrates this convention.

CONCLUSION

The use of Locus™ Machine Sub-Class Names and Parametric Error Names (PENs) has allowed the creation of an application which will create complete PEN Lists for machine errors, simply from the Sub-Class Name (Figure 4.0). These lists provide the foundation on which to build tools for Machine Modeling as well as Error Diagnostics and Correction. Test instrumentation and artifacts, with the corresponding test procedures can be easily identified and organized using the PEN List.

Machine Sub-Class Names and Parametric Error Names should be considered to extend the utilization of current National and International Standards. These extensions will simplify the interchangeability of data between the developers of Machine Metrology Software and Instrumentation.

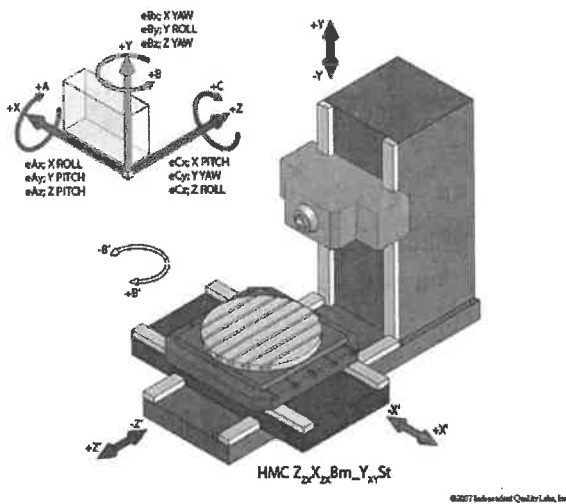


Figure 3: Horizontal Machining Center.

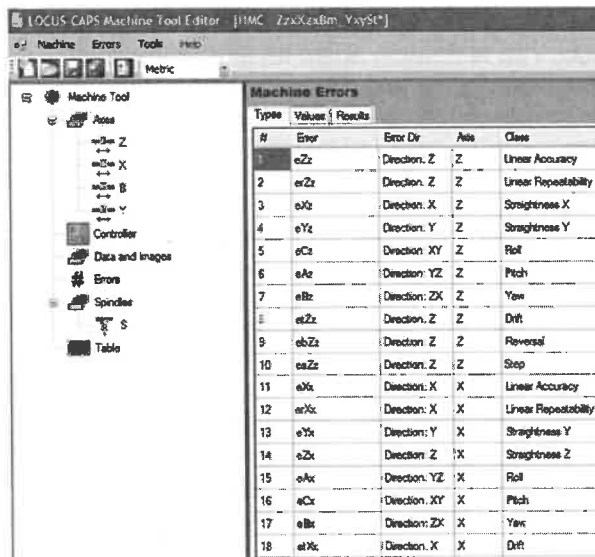


Figure 4: Locus Error View

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PROCESS DEVELOPMENT AND TROUBLESHOOTING FOR THE MANUFACTURING OF ULTRA PRECISION COMPONENTS: AN ERROR BUDGET APPROACH?

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INTRODUCTION

There are many approaches to the implementation of manufacturing processes for the production of high precision components such as optical lenses. Some approaches are successful, while other methods unfortunately fail to produce the desired results. Failure to execute an effective process development strategy can result in failure to produce the required components and can have severe economic consequences. Most often a major cause of fabrication failure, fabrication difficulty or inability to evolve a process to success is a lack of the proper approach to process development rather than limited technical or financial resources.

Process control at all levels is key to the successful manufacture of ultra precision components. Ultra precision manufacturing requires an understanding and evolution of the process in order to produce the required components, improve part quality as production increases and maintain part quality over time. One of the most difficult approaches to manufacturing is the assumption that no process development should be required, and that the only variables effecting production quality are controlled solely by the machine tool. While this view enables instant part production, it can only be successful if the parts produced are of acceptable quality and require no additional improvement, process evaluation or process understanding. This can occur if the process capability far exceeds the part quality requirements. This approach is rarely successful in ultra precision manufacturing where the part quality requirements are extreme and intense focus and control of the process and process errors are required.

APPROACHES TO PROCESS DEVELOPMENT AND TROUBLE SHOOTING

Black Box Methodology

A common approach to characterizing a manufacturing process is to run experiments that establish a mathematical model, or transfer function, between process variables as inputs and quantifiable part characteristics as outputs. The machine tool is treated as a "black box" because the physical characteristics of the machining process are not investigated. Variables deemed statistically insignificant are usually neglected in a final transfer function model.

One of several problems with a "black box" approach includes the possibility of overlooking important process variables which can lead to a misleading transfer function model. Improper error identification can, in some cases, completely block all further process improvement, trouble-shooting efforts, or process evolution, and control over the process may never be achieved. In many cases manufacturing processes are no longer considered "black box" systems. Instead they are broken down into various sub components that can include almost all error contributions within the manufacturing system.

Statistical Process Control Approach

Statistical process control is often used as a method for tracking process performance over time. One can statistically demonstrate when the process is going out of control relative to production output requirements. Once this happens, process improvement and support is triggered to reestablish process yield. This method can be very beneficial to providing evidence as to the success or failure of all production support and process development efforts.

In manufacturing environments where statistical process control is used exclusively, management is likely to make decisions based on statistical performance numbers alone. For example, if an existing machine tool only has a yield of 25 percent the decision might be made to quadruple the number of machine tools to reach the equivalent of a single machine with 100 percent yield. This type of example usually occurs in manufacturing environments where process development and process evolution are neglected, and the need for production output outweighs all other considerations.

The Integrative Approach

An integrative approach to process development does not require determination and evaluation of all the variables that influence a manufacturing process. A more direct focus is placed on the importance of producing the required part as the "bottom line" determination that a process will perform as required. This approach is common with customers of machine tool builders. The attitude taken is that if the part produced meets specification limits so does the machine tool. The assumption is that since the test part is good all contributing variables are operating within acceptable limits. In contrast the philosophy is that if the part is out of specification so is the machine tool. Generally this ignores the error contributions of other aspects of the manufacturing process.

A main problem with the integrative approach is that part quality may be initially acceptable, but may not continue to repeat. How does one troubleshoot a process where out-of-spec parts are produced sporadically? In this case, process variables must be identified and tuned to improve the part quality and, therefore, abandoning the integrative approach.

The Functional Approach

This is one of the most common and fastest approaches to manufacturing process development and troubleshooting. Often the process evaluator has some idea what causes the error in the part manufacturing process. With this approach a single process variable is changed, and a test part is recut. If the test part is in spec, the conclusion is that the correct variable was identified and properly modified. With luck the change had no adverse effects on the process and production can quickly continue. If the initial change to the process has not eliminated the problem of concern,

continuing this approach can lead to increased inability to dissect the process. As individual variables are repeatedly changed over extended time, one loses control of the original process stability and performance characteristics. It becomes almost impossible to make conclusions about the process by evaluating the quality of the test part alone.

The functional approach is impractical with ultra precision processes, where the manufacturing variables are constantly changing over time at very small levels. Maintaining constant process variables and measuring the effect of one changed variable by evaluating a test part alone is very difficult and often leads to erroneous conclusions.

The Deterministic Manufacturing Approach - An Error Budget Approach?

A very effective and successful method for the development of ultra precision manufacturing processes and analysis of part quality problems is accomplished by identifying, isolating and quantifying individual error contributors as accurately as possible. Especially with diamond turning processes, where there is a near linear relationship between process errors and part quality, it is possible to eliminate nanometer level positioning errors and observe a direct correlation in part quality. This approach also makes sense for more conventional cutting operations with steel and aluminum workpieces. The challenge is to find methods to isolate the error sources, implement instrumentation to directly measure them, and therefore avoid the necessity of using part quality data to characterize a single process variable. By developing very specific measurement techniques it becomes possible to verify when a specific error is removed. As ultra precision machining processes have evolved to higher and higher levels of accuracy, the ability to measure the error sources within the machining processes have improved correspondingly.

Sometimes apparent part quality is not changed even though verifiable error removal from the process has occurred. Patience is required in this case, and as the knowledge of the process increases with errors addressed, part quality eventually improves. There are now many examples of very highly controlled, high accuracy manufacturing processes that have been developed through the use of error source analysis and persistent error elimination. As the errors are identified and quantified, they can be compared to pre-established or allowable error

budgets for the individual error contributions. Manufacturing management can develop an understanding of the current process capability and accurately plan for higher levels of process capability if desired.

EXAMPLE: DIAMOND TURNING OPERATION OF OPTICAL CYLINDERS

Figure 1 depicts a precision turning operation of a 1.0 m long optical cylinder on a tailstock lathe and quantifiable error sources that were identified using a deterministic manufacturing approach. In the past thermal errors, such as environmental temperature variation and temperature increase of the headstock spindle were identified as major contributors to part errors [1]. In this example the temperatures of the environment, machine and workpiece were monitored by strategically placed thermistors. The headstock spindle housing was found to be a local hotspot due to the spindle motor and shear friction in the hydrostatic bearings.

To investigate potential temperature induced axial deformations of the spindle the workpiece was removed from the machine, and a spherical artifact as outlined in [2] was mounted to the spindle face. Capacitance sensors and specially designed thermally stable mounts were used to measure displacements of the spindle face (Figure 2). This allowed for a direct evaluation of the error in question by decoupling thermal expansion of the workpiece from the measurement. Figure 3 shows the displacement over time during a simulated machining run reaching a maximum of $69 \mu\text{m}$ (0.0027 in.) after 70 minutes. Corrective actions such as a spindle cooler and a process change to allow the spindle to thermally stabilize were implemented.

To further demonstrate the extreme levels of process control sometimes necessary for ultra precision machining operations an example measurement of the spindle error motions of a high quality airbearing spindle is presented in Figure 4. Spindle error motions can degrade form or surface quality of optical workpieces. As seen in the polar graph synchronous and asynchronous errors combined did not exceed 6 nm. The measurement was performed using three angularly offset capacitance sensors in the radial direction of the spindle that enabled the subtraction of inherent roundness errors of the master ball artifact mounted to the spindle face [3].

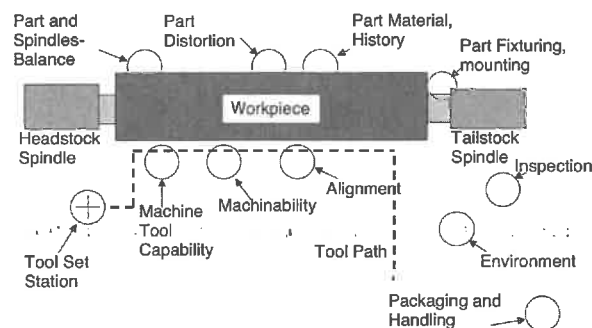


Figure 1: Process variables and potential error sources in a precision turning operation with a tailstock lathe.

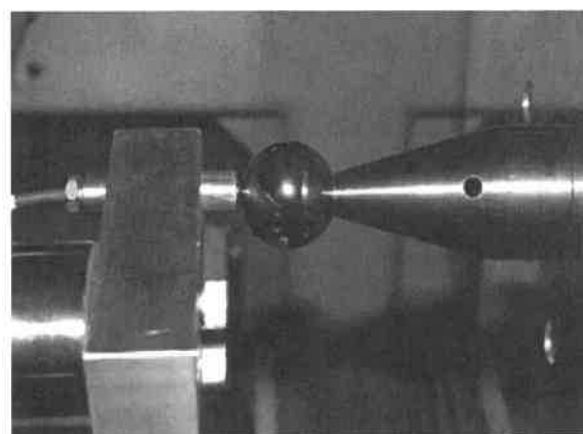


Figure 2: Measurement of axial spindle drift using a spherical artifact and a capacitance probe on a low CTE mount.

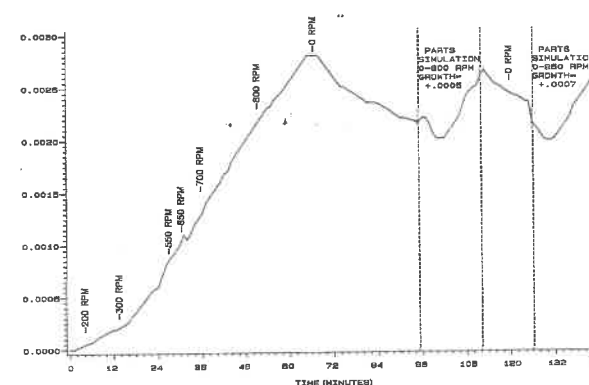


Figure 3: Total axial spindle growth in inches during a typical machining run.

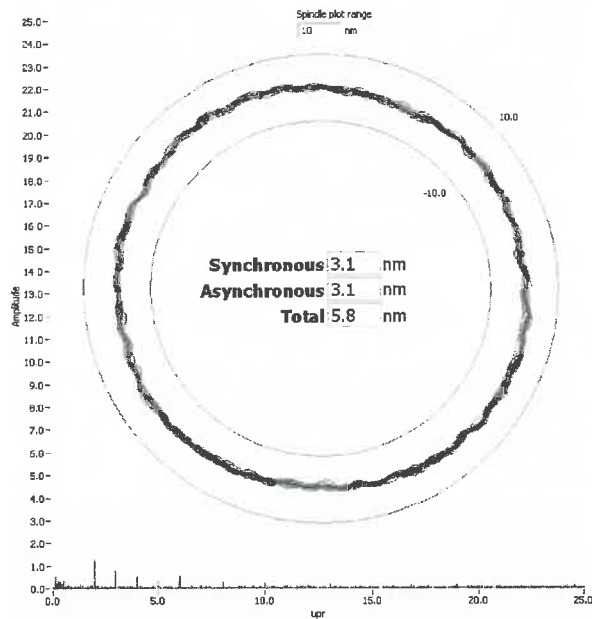


Figure 4: Polar graph and spectrum of radial spindle error motions of high quality airbearing spindle (courtesy of Professional Instruments Inc., Lion Precision Inc.)

CONCLUSIONS

Manufacturing processes in general are no longer modeled as “black boxes” where experiments are required to evaluate the effects of process variable changes on part quality. Many direct measurement methods have been developed which enable separation and direct evaluation of errors. As process variables are optimized improvements to the process are documented by verifying the reduction of specific errors. Only a deterministic approach can enable sustained evolution and development of a manufacturing process. Rather than searching for “the problem” individual error sources should be isolated and their significance on part quality quantified (“cause determines effect”). The manufacturing process is then steadily improved by eliminating individual process error sources one by one. As the error contributions are charted a view of the manufacturing process capability is developed, and an understanding of the potential to improve the process capability is understood. Part quality data or test parts are only utilized to track performance and verify process improvements but not to evaluate or troubleshoot a manufacturing process.

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